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HOT CARRIERS IN SEMICONDUCTORS 6

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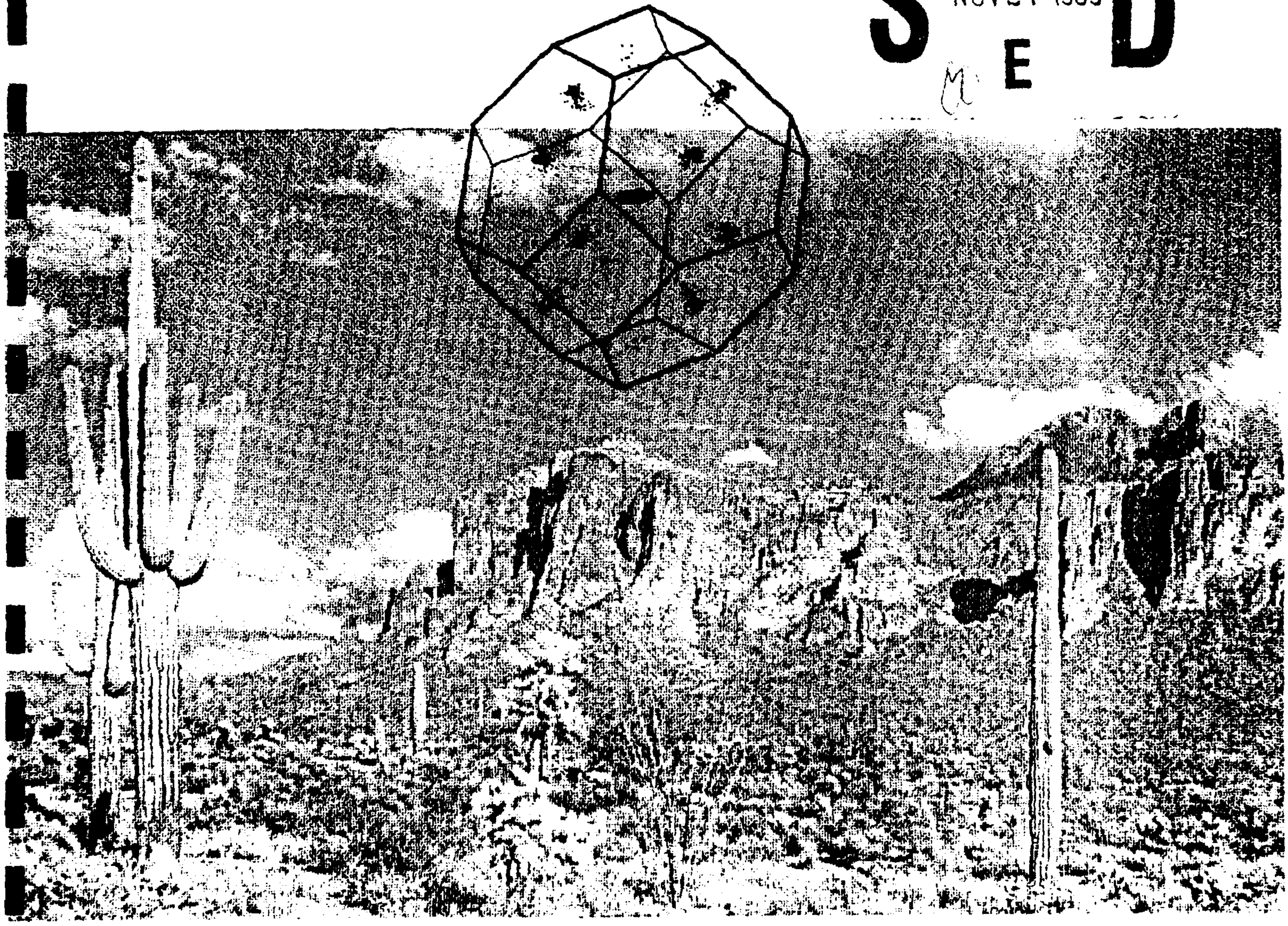

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The conference on Hot Carriers in Semiconductors was held as scheduled. This report provides abstracts of the presentations.

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Hot Carriers in Semiconductors

Monday, July 24

9:00 a.m. General Welcome and Overview - *D. K. Ferry, Arizona State Univ.*

Session MA, *Gerald J. Iafrate*, Chairman

9:20 **I-1** "Resonant Tunneling in Heterojunction Barriers," *Laurence Eaves*, Nottingham

10:05 **I-2** "Multivalued hot electron distributions as spontaneous symmetry breaking," *Marian Asche*, Berlin

10:40 Coffee Break

Session MB - Far Infrared Studies, *Erick Gornik*, Chairman

11:10 **MB-1** "Intersubband emission from superlattices," *M. Helm, P. England, E. Colas, F. DeRosa, and S. J. Allen, Jr.*, Red Bank

11:30 Poster "shotgun" session - 2 min. per speaker

MP-1 "Far infrared radiation induced photovoltage of inversion electrons on GaAs," *F. Thiele, E. Batke, J. P. Kotthaus, V. Dolgopolov, G. Weimann, W. Schlapp*, Hamburg

MP-2 "Tunable cyclotron-resonance laser based on hot holes in germanium applied to FIR-spectroscopy of GaAs heterostructures," *K. Unterrainer, C. Kremser, E. Gornik, Yu. L. Ivanov*, Innsbruck

MP-3 "FIR NDC under hot electron intervalley transfer," *A. Andronov and I. Nefedov*, Gorky

MP-4 "Frequency range and distributions of inverted hot hole generated FIR in germanium," *V. I. Gavrilenko, N. G. Kalugin, Z. F. Krasil'nik, and V. V. Nikonorov*, Gorky

MP-5 "Smith-Purcell-emission from a drifting 2D-carrier gas in GaAs," *E. Gornik, D. Weiss, G. Wolff, G. Weimann, R. Christanell, and W. Beinstingl*, München

12:00 *BREAK FOR LUNCH*

Session MC - Low Dimensional Systems and Superlattices, *P. Lugli*, Chairman

2:00 p.m. **I-3** "Nonequilibrium effects in quasi-one dimensional weak localization," *T. Ikoma*, Tokyo

2:30 p.m. **MC-1** "Hot electron transport in high-lying minibands in semiconductor superlattices," *P. England, J. R. Hayes, E. Colas, and M. Helm*, Red Bank

2:50 p.m. **MC-2** "High-field transport and NDR with hot phonons in degenerate semiconductors," *R. Gupta and B. K. Ridley*, Colchester

3:10 p.m. **MC-3** "Magneto-phonon resonances in the effective temperature of photo-excited carriers in GaAs/(Ga,Al)As quantum wells," *H. A. J. M. Reinen, T. T. J. M. Berendschot, P. C. M. Christiansen, H. J. A. Bluyssen, and H. P. Meier*, Nijmegen

3:30 Break for Coffee

3:50 p.m. **MC-4** "The one-dimensional quantized ballistic resistance in GaAs/AlGaAs heterojuntions with varying experimental conditions;" *R. J. Brown, M. J. Kelly, R. Newbury, M. Pepper, D. G. Hasko, H. Ahmed, D. C. Peacock, D. A. Ritchie, J. E. F. Frost, and G. A. C. Jones*, Cambridge

4:10 p.m. **MC-5** "Non-linearity and intersubband population inversion in quantum wire structures," *S. Briggs, D. Jovanovic and J. P. Leburton*, Urbana

4:30 p.m. Poster "shotgun" session - 2 min. per speaker

MP-6 "Strong electric field [illegible] on weak localization," *G. Y. Hu and R. F. O'Connell*, Baton Rouge

MP-7 "Spatial anisotropy of the phonon emission by a hot two-dimensional electron gas in a GaAs/AlGaAs heterojunction," *P. Hawker, A. J. Kent, O. H. Hughes, and L. J. Challis*, Nottingham

MP-8 "Enhancement of energy relaxation rates in semiconductor superlattices," *M. P. Chamberlin and M. Babiker*, Colchester

MP-9 "Inelastic scattering effects on carrier relaxation in quantum-well-based hot electron structures," *R. Jalabert and S. Das Sarma*, College Park

MP-10 "Electron-electron scattering in AlGaAs/GaAs 2DEG systems under hot-electron conditions," *A. H. Guerrero*, Fort Monmouth

MP-11 "Real space transfer rates for polar optical phonon scattering from asymmetric quantum wells," *C. S. Lent and L. Liang*, Notre Dame

MP-12 "Monte Carlo simulation of hot electrons in InAlAs/InGaAs heterojunctions," *E. Kobayashi, T. Matsuoka, K. Taniguchi, and C. Hamaguchi*, Osaka

MP-13 "Geometric effects of scattering in microstructures," *A. M. Kriman, R. P. Joshi, B. S. Haukness, and D. K. Ferry*, Tempe

MP-14 "Modulation of impurity scattering rates by wavefunction engineering in quasi-2D systems and its device applications," *S. Bhobe, W. Porod, and S. Bandyopadhyay*, Notre Dame

MP-15 "Time-of-flight experiments on 2D electron gases," *E. A. E. Zwaal, W. T. Gorissen, R. M. Y. Ruber, and J. H. Wolter*, Eindhoven

MP-16 "Splitting and shift of the hot magneto-phonon resonance peaks," *P. Warmenbol, F. M. Peeters, and J. T. Devreese*, Antwerpen

MP-17 "High field mobility of light holes in strained InGaAs quantum wells," *H. P. Hjalmarson, I. J. Fritz, and L. R. Dawson*, Albuquerque

MP-18 "Negative differential perpendicular velocity in GaAs/AlAs superlattices," *A. Sibille, J. F. Palmier, F. Mollot, and J. C. Esnault*, Bagneux

MP-19 "Calculations of Zener interminiband tunneling rates in superlattices," *A.Sibille*, Bagneux

MP-20 "Experimental analysis of diffusion noise in two-dimensional electron layers in HEMTs," *J. Zimmermann, H. Kabbaj, , J. Gest, M. de Murcia, and D. Gasquet*, Villeneuve d'Ascq

MP-21 "Carrier capture in quantum wells and its importance for ambipolar transport," *T. Kuhn and G. Mahler*, Stuttgart

MP-22 "Electron capture in quantum wells: Monte Carlo simulations of transport in infrared photodetectors," *M. Artaki and I. C. Kizilyalli*, Allentown

MP-23 "Indirect excitation processes in two strongly coupled wells," *F. Clerot, B. Deveaud, B. Lambert, A. Chomette, A. Regreny, and B. Sermage*, Lannion

MP-24 "Energy relaxation of light holes in InAsSb/InSb multiple quantum wells," *C. P. Tigges, J. E. Schirber, H. P. Hjalmarson, I. J. Fritz, and L. R. Dawson*, Albuquerque

MP-25 "Energy relaxation in GaInAs/InP heterojunctions and GaAs/AlGaAs multiple quantum wells," *A. J. Vickers and A. Straw*, Colchester

MP-26 "Hot electron energy relaxation via acoustic phonon emission in GaAs/AlGaAs single and multiple quantum wells," *M. E. Daniels, B. K. Ridley, and M. Emeny*, Colchester

MP-27 "Experimental and theoretical study of scattering mechanisms for 2D excitons in GaAs/GaAlAs quantum wells," *H. Hilmer, A. Forchel, S. Hansmann, M. Morohasi, H. Meier, and K. Ploog*, Stuttgart

MP-28 "Hot electron electroluminescence in AlGaAs/GaAs heterostructures," *C. L. Petersen, M. R. Frei, and S. A. Lyon*, Princeton

MP-29 "Cyclotron phonon emission and electron energy loss rates in GaAs-GaAlAs heterojunctions," *D. R. Leadley, R. J. Nicholas, J. J. Harris, and C. T. Foxon*, Oxford

5:30 p.m. Viewing of posters **MP**

6:30 p.m. Mexican Buffet, Poolside

Tuesday, July 25

Session TuA - Optical Studies of Fast Processes I, *Jeff Young*, chairman

9:00 a.m. **I-4** "Femtosecond Excitations in Modulation-Doped quantum Wells," *Wayne Knox*, Murray Hill

9:30 a.m. **I-5** "Picosecond relaxation in quantum well systems," *John Ryan*, Oxford

10:15 a.m. **TuA-1** "Plasma instabilities in quasi two-dimensional electron gases," *J. B. Stark and P. A. Wolff*, Cambridge

10:35 a.m. Break for Coffee

10:55 a.m. **TuA-2** "Γ-X intervalley-interlayer scattering rates in type II GaAs/AlAs superlattices," *J. Feldman, R. Sattman, E. O. Göbel, J. Kuhl, J. Hebling, K. Ploog, R. Muralidharan, P. Dawson, and C. T. Foxon,* Marburg

11:15 a.m. **TuA-3** "Photoluminescence of hot electrons in A_3B_5 semiconductors and QW structures. Determination of scattering times on the femtosecond time scale," *D. N. Merlin*, Leningrad

11:35 a.m. Poster session - 2 min. per speaker

TuP-1 "Barrier controlled hot carrier cooling in InGaAs/InP quantum wells," *U. Cebulla, G. Bacher, A. Forchel, D. Grützmacher, and W. T. Tsang*, Stuttgart

TuP-2 "Time-resolved anti-Stokes Raman scattering from electronic excitations in GaAs quantum wells," *M. Tatham, J. F. Ryan, and C. T. Foxon*, Oxford

TuP-3 "Hot phonons in quantum well systems," *P. Lugli, P. Bordone, S.Gualdi, P. Poli, and S. M. Goodnick*, Rome

TuP-4 "Dynamics of the inter-subband relaxation of thermalized carriers in GaAs/AlGaAs multiple quantum wells," *J. A. Levenson, G. Dolique, J. L. Oudar, and I. Abram*, Bagneux

TuP-5 "Intersubband relaxation of hot carriers in semiconductor quantum wells," *J. Lary, S. M. Goodnick, and P. Lugli*, Corvallis

TuP-6 "Quasi-analytical simulation of ultrafast relaxation of photo-excited electrons in a semiconductor quantum well," *T. F. Zheng, W. Cai, P. Hu, and M. Lax*, New York

TuP-7 "Monte Carlo simulation of femtosecond spectroscopy in semiconductor heterostructures," *S. M. Goodnick, P. Lugli, W.H. Knox, and D. S. Chemla*, Corvallis

TuP-8 "Intersubband dynamics in modulation doped quantum wells," *J. L. Educato, A. Sugg, D. W. Bailey, K. Hess, and J.P. Leburton*, Urbana

TuP-9 "Intersubband absorption of hot electrons in a modulation doped GaInAs/AlInAs multiple quantum well," *T. Elsaesser, R. J. Bauerle, H. Lobentanzer, W. Stolz, and K. Ploog*, Munich

TuP-10 "Hot carrier thermalization in GaAs/AlAs superlattices," *K. Leo, W. W. Rühle, and K. Ploog*, Stuttgart

TuP-11 "Screening of the n=2 excitonic resonance by hot carriers in an undoped GaInAs/AlInAs multiple quantum well structure," *H. Lobentanzer, W. Stolz, K.Ploog, T. Elsaesser, and R. J. Bäuerle*, Stuttgart

12:00 *BREAK FOR LUNCH*

Session TuB - Hot Carriers in Bulk Materials, *Helmut Heinrich*, Chairman

2:00 p.m. **I-6** "Nonequilibrium carrier noise and its effects in microstructures," *V. L. Gurevich*, Leningrad

2:30 p.m. **TuB-1** "Are transverse phonons important for intervalley scattering?" *S. Zollner, J. Kircher, M. Cardona, and S. Gopalan*, Stuttgart

2:50 p.m. **TuB-2** "Hot electron magnetophonon spectroscopy of semiconductors in high magnetic fields up to 40 T," *K. Yamada, N. Miura, C. Hamaguchi, and N. Kamata*, Tokyo

3:10 Coffee Break

3:30 p.m. Poster "shotgun" session - 2 min. per speaker

TuP-12 "Polar-optical-phonon scattering of charge carriers in alloy semiconductors: effects of phonon localization," *L. F. Register, M. A. Littlejohn, and M. A. Stroscio*, Raleigh

TuP-13 "Hot phonon-hot electron coupled Boltzmann equations in GaAs and in InP," *M. Fadel, M. Rieger, J. C. Vaissiere, J.P. Nougier, and P. Kocevar*, Montpellier

TuP-14 "A many-band silicon model for hot-electron transport at high energies," *R. Brunetti, C. Jacoboni, F. Venturi, E. Sangiorgi, and B. Ricco*, Modena

TuP-15 "Effect of the degeneracy on the transport of hot holes in silicon," *A. Moatadid, J. C. Vaissiere, and J. P. Nougier*, Montpellier

TuP-16 "Weighted ensemble Monte Carlo," *L. Rota, C. Jacoboni, and P. Poli*, Modena

TuP-17 "Direct Monte Carlo simulation of hot-carrier conductivity," *L. Reggiani, L. Varani, and V. Mitin*, Modena

TuP-18 "Energy exchange via electron-electron scattering in many-valley semiconductors," *L. Rota and P. Lugli*, Modena

TuP-19 "Electron-beam induced conductivity at high electric fields in GaAs," *C. Panhuber, H. Heinrich, H. Thim, and K. Lübke*, Linz

TuP-20 "Photoemission of metal-semiconductor structures: novel spectroscopy for high speed transport," *J. Peretti, D. Paget, and H. J. Drouhin*, Palaiseau

TuP-21 "Transverse diffusion coefficient and carrier density fluctuation derived from the fluctuation of the state occupancy function in semiconductors," *J. P. Nougier and J. C. Vaissiere*, Montpellier

TuP-22 "Autosolitons in electron-hole plasma weakly heated by an electric field," *M. N. IVinoslavskii, B. S. Kerner, V V. Osipov, and C. G. Sarbei*, Kiev

TuP-23 "Excitation spectra of photoinjected hot carriers," *A. S. Esperidião, A. R. Vasconcellos, and R. Luzzi*, Salvador

TuP-24 "The hot electron kinetics in gapless semiconductors: the influence of LO-phonon interband transitions," *A. V. Dmitriev*, Moscow

Session TuC - Quantum Transport and Modeling, *C. Jacoboni*, chairman

4:00 p.m. **I-7** "Nonequilibrium Green's function techniques applied to hot electron quantum transport," *A. P. Jauho*, Copenhagen

4:30 p.m. Poster Session - 2 minute presentations

TuP-25 "Position broadening effect in hot-electron transport," *R. Bertoncini, A. M. Kriman, D. K. Ferry, L. Reggiani, and A. P. Jauho*, Tempe

TuP-26 "Hot carrier effects in quantum-confined devices," *G. J. Iafrate and J. B.*

Krieger, Fort Monmouth

TuP-27 "A Broad theoretical approach to the investigation of mesoscopic electron devices," *U. Ravaioli, F. Sols, and T. Kerkhoven*, Urbana

TuP-28 "Theory of nonlinear transport in quantum waveguides," *J. M. Barker, M. Laughton, and J. Nixon*, Glasgow

TuP-29 "Theory of ballistic electron transport through quantized constrictions," *S. He and S. Das Sarma*, College Park

TuP-30 "A two-dimensional hot carrier injector for electron waveguide structures," *C. S. Lent, S. Sivaprakasam, and D. J. Kirkner*, Notre Dame

TuP-31 "Effective potential for moment-method simulation of quantum devices," *H.H. Choi, J. Zhou, N. C. Kluksdahl, A. M. Kriman, and D. K. Ferry*, Tempe

TuP-32 "Quantum moment balance equations and resonant tunneling structures," *H. L. Grubin and J. P. Kreskovsky*, Glastonbury

TuP-33 "A quantum description of drift velocity overshoot at high electric fields in semiconductor," *F. Rossi and C. Jacoboni*, Modena

TuP-34 "Impurity scattering in quantum transport simulation," *C. Jacoboni, P. Menziani, and F. Rossi*, Modena

5:00 poster viewing

6:30 Steakfry, Mummy Mountain Western Village

Wednesday, July 26

Session WA - Resonant Tunneling, *M. J. Kelly*, Chairman

9:00 a.m. **I-8** "Hot Electrons in Resonant Tunneling Diodes," *Elliott Brown*, Lexington

9:45 a.m. **WA-1** "Tunneling between two quantum wells: InGaAs/InP vs. GaAs/AlGaAs," *M. G. W. Alexander, W. W. Rühle, R. Sauer, W. T. Tsang, K. Ploog, and K. Köhler*, Stuttgart

10:05 a.m. **WA-2** "Transient Analysis of Resonant Tunneling Hot Electron Transistor (RHET)," *H. Ohnishi, N. Yokoyama, and A. Shibatomi*, Atsugi

10:25 Coffee break

10:45 a.m. **WA-3** "Energy spectroscopy of electron distributions injected by a double barrier resonant tunneling structure," *M. Heiblum, U. Sivan, and M. V. Weckwerth*, Yorktown Heights

11:05 a.m. **WA-4** "Tunneling and energy-relaxation of hot electrons in double-quantum well structures," *N. Sawaki, R. Höpfel, E. Gornik, and H. Kano*, Innsbruck

11:25 a.m. **WA-5** "Do the X point minima affect the transport properties of resonant tunneling devices?," *T. J. Foster, M. L. Leadbeater, E. S. Alves, L. Eaves, M. Henini, O. H. Hughes, A. Celeste, J. C. Portal, D. Lancefield, A. R. Adams, G. Hill, and A. M. Pate*, Nottingham

11:45 p.m. Poster session - 2 min. per speaker

WP-1 "X-point tunneling in AlAs-GaAs-AlAs double barrier heterostructures," *D. Z.-Y. Ting and T. C. McGill*, Pasadena

WP-2 "A new inverted bistability effect in asymmetric double barrier structures," *M. L. Leadbeater, L. Eaves, M. Henini, O. H. Hughes, G. Hill, and M. A. Pate* , Nottingham

WP-3 "Analysis of defect-assisted tunneling in AlGaAs/GaAs resonant tunnel diodes based on low frequency noise measurements," *M. H. Weichold, S. S. Villareal, and R. A. Lux*, College Station

WP-4 "DC and AC analysis of high current double barrier structures," *O. Vanbesien and D. Lippens*, Villeneuve d'Ascq

WP-5 "Space-charge effects and a.c. response of resonant-tunneling double-barrier diodes," *F. W. Sheard and G. A. Toombs*, Nottingham

WP-6 "Role of structure sizes in determining the frequency characteristics of the resonant tunneling diode," *N. C. Kluksdahl, A. M. Kriman. and D. K. Ferry*, Tempe

WP-7 "Large peak-to-valley ratios in triple barrier hetereostructures," *D. A. Collins, D. H. Chow, D. Z. Ting, E. T. Yu, J. R. Söderstrom, and T. C. McGill*, Pasadena

WP-8 "Effect of inelastic processes on the self-consistent potential in the resonant-tunneling diode," *W. R. Frensley*, Dallas

WP-9 "InAs-mode LO phonon emission assisted tunneling in InGaAs/AlInAs double barrier structures," *A. Celeste, L. A. Cury, J. C. Portal, M. Allowon, D. K. Maude, and L. Eaves*, Toulouse

WP-10 "Design, fabrication and operation of a hot lectron resonant tunneling transistor," *U. K. Reddy, I. Mehdi, R. K. Mains, and G. I. Haddad*, Ann Arbor

WP-11 "Investigation of the voltage at the peak position as a function of the transversal magnetic field in a double-barrier resonant tunneling current. The importance of k_y-value at low fields," *L. A. Cury, A. Celeste, J. C. Portal, E. S. Alves, M. L. Leadbeater, L. Eaves, G. Hill, and M. A. Pate*, Grenoble

WP-12 "Resonant tunneling through magnetic edge states," *F. M. Peeters, M. Helm, P. England, J. R. Hayes, E. Colas, J. P. Harbison, and L. T. Flores,* Red Bank

WP-13 "Resonant tunneling in crossed electric and magnetic fields: a tool fo investigating extreme hot electron effects," *J. R. Hayes, P. England, M. Helm, J. P. Harbison, L. T. Flores, and S. J. Allen, Jr.,* Red Bank

WP-14 "A self-consistent model of magneto-tunneling," *W. Pötz and J. Zhang,* Chicago

WP-15 "Disorder effects on resonant tunneling in quantum-well heterostructures," *Z. G. Li and W. Pötz,* Chicago

Break for free afternoon

Session WB - Chaos, Instabilities, and Impact Ionization, *N. Sawaki*, chairman

8:00 p.m. **I-9** "Dynamics of moving space charge domains in Ge at liquid He temperatures," *Robert Westervelt, A. Kahn, and D. Mar,* Cambridge

8:30 p.m. **I-10** "Space charge currents, domains, and instabilities viewed with voltage contrast spectroscopy," *George Maracas,* Tempe

9:00 p.m. **I-11** "From hot electron transport theory to macroscopic nonlinear and chaotic behavior by impact ionization in semiconductors," *Eckehard Schöll,* Aachen

9:30 p.m. Poster "shotgun" session - 2 min. per speaker

WP-16 "Imaging of spatio-temporal transport structures in semiconductors," *U. Rao, K. M. Mayer, J. Parisi, J. Peinke, and R. P. Hübener,* Tübingen

WP-17 "Complex dynamical behavior and chaos in the Hess oscillator," *K. Aoki, K. Yamamoto, N. Mugibayashi, and E. Schöll,* Kobe

WP-18 "Current-controlled hot-electron instability in the three-terminal heterostructure device," *A. Kastalsky, M. Milshtein, L. G. Shantharama, and J. Harbison,* Red Bank

WP-19 "Hot phonons and instabilities in GaAs/GaAlAs structures," *N. Balkan, B. K. Ridley, M. Emeney, J. Roberts, and I. Goodridge,* Colchester

WP-20 "Hot electrons and traps in a-SiO_2," *R. Kamocsai and W. Porod,* Notre Dame

WP-21 "Space-charge anomalies in insulators caused by non-local impact ionization," *B. K. Ridley and F. A. El-Ela,* Colchester

WP-22 "Spontaneous oscillations and chaos in Si induced by excitonic impact ionization," *H. Weman, A. Henry, and B. Monemar*, Linköping

WP-23 "Impact ionization breakdown in p-germanium samples with very short contact distances," *W. Clauss, J. Peinke, J. Parisi, and R. P. Hübener*, Tübingen

WP-24 "Resonant impact ionization in bismuth-antimony semiconductors at quantizing magnetic fields," *E. V. Bogdanov*, Moscow

WP-25 "Instabilities and negative magnetoresistance in HgCdTe semiconductors at avalanche breakdown," *E. V. Bogdanov*, Moscow

PDP-4 "Global bifurcation and hysteresis of self-generated oscillations in a microscopic model of nonlinear transport in p-Ge," *G. Hüpper, E. Schöll, and L. Reggiani*, Aachen and Modena

9:50 poster viewing

Thursday, July 27

Session ThA - Semiconductor Devices I, *J. Zimmermann*, Chairman

9:00 a.m. **I-12** "Electron energy spectroscopy, spatial distributions, and the observation of ballistic transport of hot electrons in the plane of a 2DEG," *A. Palevski, U. Sivan, M. Heiblum, and C. P. Umbach*, Yorktown Heights

9:30 a.m. **I-13** "Nonequilibrium electron dynamics in small semiconductor structures," *A. F. J. Levi*, Murray Hill

10:00 a.m. **ThA-1** "Very highly energy-resolved ballistic electron spectroscopy in a device capable of multi-state logic," *S. J. Bending, A. J. Peck, K. v. Klitzing, P. Gueret, and H. P. Meier*, Stuttgart

10:20 a.m. Coffee Break

10:40 a.m. **ThA-2** "Optical analysis of real space hot electron distributions in heterolayers," *M. Inoue, R. Sakamoto, and K. Akai*, Osaka

11:00 a.m. **ThA-3** "New features of real-space hot-electron transfer in the NERFET," *A. Kastalsky, L. G. Shantharama, M. Milshtein, and J. Harbison*, Red Bank

11:20 Poster "shotgun" session - 2 min. per speaker

ThP-1 "Ballistic hot electron transport in n-AlGaAs/GaAs double barriers with wide wells," *E. S. Alves, M. L. Leadbeater, M. Henini, L. Eaves, and O. Hughes*, Nottingham

ThP-2 "Lateral space-charge effects on ballistic electron transport across graded heterojunctions," *S. Weinzierl and J. P. Krusius*, Ithaca

ThP-3 "Hot electron injection in millimeter wave Gunn diodes," *N. R. Couch, M. J. Kelly, H. Spooner, and T M. Kerr*, Wembley

ThP-4 "Effective velocity-field characteristics in submicron GaAs MESFETs including near ballistic transport," *Y. Yamada*, Kumamoto

ThP-5 "Hydrodynamic hot-electron transport simulations of enhanced transit times in submicron N^+-N-P^+-N-N^+ GaAs device structures," *D. L. Woodard, R. J. Trew, M. A. Littlejohn, and C. T Kelley*, Raleigh

ThP-6 "Monte Carlo simulation of AlGaAs/GaAs heterostructure MIS-like FET accounting for the gate current," *R. Fauquembergue, J. L. Thobel, K. Bellahsni, P Bourel, and M. Pernisek*, Villeneuve d'Ascq

ThP-7 "Two-dimensional simulation of sub-μm GaAs MESFETs with ion-implanted doping," *Y. K. Feng and K. Schünemann*, Hamburg

ThP-8 "Interface state generation mechanism in n MOSFETs," *N. Yasuda, H. Nakamura, K. Taniguchi, and C. Hamaguchi*, Osaka

ThP-9 "Light emission from hot carriers in FET-devices," *M. Herzog, F. Koch, C. Moglestue, and J. Rosenzweig*, München

PDP-1 "Hot electron focusing with quantum point contacts," *J. G. Williamson, H. van Houten, C. W. J. Beenakker, L. I. A. Spendeler, B. J. van Wees, and C. T. Foxon*, Eindhoven

PDP-2 "Length dependent hot electron noise in GaAs and InP at 80 K," *V. Bareikis, J. Liberis, A. Matulionis, R. Miliusyte, J. Pozela, and P. Sakalas*, Vilnius

PDP-3 "Phonon-assisted tunnelling of photoexcited carriers from InGaAs quantum wells in applied electric fields," *M. G. Shorthose, J. F. Ryan, and A. Moseley*, Oxford

PDP-5 "Addition of Ballistic Resistors," *P. Beton, B. R. Snell, A. Neves, P. C. Main, J. R. Owens-Bradley, L. Eaves, M. Henini, C. H. Hughes, S. P. Beaumont, and C. D. W. Wilkinson*, Nottingham

PDP-6 "Wavepacket propagation in an arbitrary two-dimensional configuration," *M. Cahay, J. P. Kreskovsky, and H. L. Grubin*, Glastonbury

PDP-7 "Hot electron scattering rates in quasi-equilibrium electron-hole plasmas calculated using full dynamic screening," *J. F. Young, P. J. Kelly, and N. L. Henry*, Ottawa

12:00 *BREAK FOR LUNCH*

Session ThB - Fast Processes in Semiconductors II, *Jeff Kash,* Chairman

2:00 p.m. **I-14** "Femtosecond processes in semiconductors," *Jagdeep Shah,* Murray Hill

2:45 p.m. **ThB-1** "Femtosecond electron and hole thermalization in AlGaAs," *R. A. Taylor, C. W. W. Bradley, and J. F. Ryan,* Oxford

3:05 p.m. **ThB-2** "Fast, alloy-disorder-induced intervalley scattering in AlGaAs," *H. Kalt, W. W. Rühle, and K. Reimann,* Stuttgart

3:25 p.m. Coffee break

3:45 p.m. **ThB-3** "Quantitative measurements of intervalley and carrier-carrier scattering in GaAs with hot (e,A^0) luminescence," *J. A. Kash, R. G. Ulbrich, and J. C. Tsang,* Yorktown Heights

4:05 p.m. **ThB-4** "Determination of the LO phonon and the Γ-L scattering time in GaAs from CW hot luminescence spectroscopy," *W. Hackenberg, G. Fasol, H. P. Hughes, E. Bauser, and K. Ploog,* Cambridge

4:25 Poster "shotgun" session - 2 min. per speaker

ThP-10 "The intervalley X-Γ scattering time in GaAs measured by pump-IR-probe infrared absorption spectroscopy," *W. B. Wang, N. Ockman, M. Yan, and R. R. Alfano,* New York

ThP-11 "Picosecond photoluminescence measurements of hot carrier relaxation and Auger recombination in GaSb," *P. A. Snow, D. J. Westland, J. F. Ryan, and P. Maly,* Oxford

ThP-12 "Nonthermalized carrier distributions in systems with extremely short lifetimes," *R. A. Höpfel,* Innsbruck

ThP-13 "Carrier cooling in nonpolar semiconductors studied with subpicosecond time resolution," *A. Seilmeier, H. Roskos, B. Rieck, and W. Kaiser,* München

ThP-14 "Hot carrier relaxation in InP and GaAs on a subpicosecond time scale," *X. Q. Zhou, K. Seibert, W. Kütt, K. Wolter, and H. Kurz,* Aachen

ThP-15 "Relaxation of hot carriers in undoped and n-doped GaInAs generated by subpicosecond IR-pulses," *H. Roskos, B. Rieck, A. Seilmeier, and W. Kaiser,* München

ThP-16 "Hot-carrier dynamics in Ge on single picosecond timescales. orrelating Raman and reflectivity experiments within a self-consistent model," *J. F. Young, P. J. Kelly, A. Othonos, and H.M. van Driel,* Ottawa

ThP-17 "Transport of the photoexcited electron-hole plasma in InP," *K. T. Tsen, G. Halama, O. F. Sankey, and S. C. Y. Tsen,* Tempe

ThP-18 "Picosecond free carrier absorption and hot phonons in polar semiconductors," *T. Elsaesser, R. J. Bäuerle, and W. Kaiser,* München

ThP-19 "Electron-electron scattering modifications of intervalley transition rates and ultrafast relaxation of hot photoexcited carriers in GaAs," *M. J. Kann, A. M. Kriman, and D. K. Ferry,* Tempe

ThP-20 "A self-consistent Monte Carlo method for the transient response of laser excited photoconductive circuits," *R.Joshi and R. O. Grondin,* Tempe

ThP-21 "Effect of valence band anisotropy on the ultrafast relaxation of photoexcited carriers in GaAs," *M. A. Osman, M. Cahay, and H. L. Grubin,* Glastonbury

ThP-22 "Femtosecond studies of intervalley scattering in GaAs and AlGaAs," *C. J. Stanton, D. W. Bailey, K. Hess, M. J. LaGasse, R. W. Schoenlein, and J. G. Fujimoto,* Gainesville

ThP-23 "Time-domain finite-difference study of hot carrier transport in GaAs on a subpicosecond scale," *Y. Lu, R. Joshi, S. El-Ghazaly, and R. O. Grondin,* Tempe

ThP-24 "Electron transport in semiconductors under a strong high frequency electric field," *W. Cai, P. Hu, T. F. Zheng, B. Yudanin, and M. Lax,* New York

5:00 poster viewing

6:30 Reception, Ballroom Foyer

7:30 Conference Banquet, Ballroom

Friday, July 28

Session FA - Semiconductor Devices II, *W. Porod*, Chairman

9:00 a.m. **I-15** "Monte Carlo simulation of hot-carrier transport in *real* semiconductor device," *Massimo Fischetti, S. E. Laux, D. Ahn, and D. J. Frank*, Yorktown Heights

9:30 a.m. **I-16** "Experimental study of hot carriers in small size Si-MOSFETs," *Akira Toriumi*, Kawasaki

10:00 a.m. **FA-1** "Overshoot saturation in ultra-short channel FETs due to minimum acceleration length," *J. M. Ryan, J. Han, A. M. Kriman, D. K. Ferry, and P. Newman*, Tempe

10:20 Coffee Break

10:40 a.m. **FA-2** "Ensemble Monte Carlo simulation of sub-0.1μm gate length GaAs MESFETs," *M. Kuzuhara, T. Itoh, and K. Hess*, Kanagawa

11:00 a.m. **FA-3** "Lattice gas theory of semiconductor transport," *M. Rieger and P. Vogl*, Graz

11:20 a.m. **FA-4** "Novel mobility-controlled switching effect in a heterojunction structure," *F. Capasso, F. Beltram, and R. J. Malik*, Murray Hill

Session FB - Closing Remarks, *D. K. Ferry, Chairman*

11:40 a.m. **FB-1** "Summary of the Conference," *Peter Price*, Yorktown Heights

12:00 **FB-2** "The future of hot carriers," *Gerry Iafrate*, Fort Monmouth

I-1 Resonant tunneling in semiconductor heterostructures, L. Eaves, *University of Nottingham, United Kingdom.* Hot electron effects are important in double barrier resonant tunneling devices because electrons are in general injected into and out of the well at high kinetic energy. This talk will examine how the use of high magnetic fields can provide detailed information about hot carrier relaxation. The topics discussed will include (1) tunneling assisted by LO phonons, (2) experimental evidence for the sequential tunneling model, (3) intrinsic bistability, (4) tunneling into high energy hybrid magneto-electric subbands.

I-2 Multivalued hot electron distributions as spontaneous symmetry breaking, M. Asche, *Zentralinst. Elektronenphysik AdW, Berlin.* In a many-valley semiconductor subject to an electric field strength above a critical value F_c, i.e. under strongly nonlinear conditions, transverse fluctuations may lead to a repopulation of the valleys, even if these are equally oriented with respect to the applied field. This spontaneous symmetry breaking leads to a stable state, in which the various distributions coexist in neighboring regions with boundaries parallel to the current, each characterized by its anisotropic conductivity and exhibiting a transverse field, consequently. In turn negative differential conductivity occurs in the vicinity of F_c.

In "long" samples the transverse fields caused by the symmetry breaking can achieve values of the order of the applied fields and the positions of the walls between the different regions are very sensitive to external disturbances and can be switched by these influences (magnetic field, light, uniaxial pressure). The experimental results for Si with respect to the transverse fields as well as ndc agree very well with the theoretical predictions and with Monte Carlo calculations.

In "short" samples a structure with many alternating domains of opposite anisotropy is realized. Small deviations of the crystallographic orientation from the symmetry direction, or the presence of a magnetic field, lead to a movement of the domains and therefore yield an a.c. voltage at the side probes, the frequency of which depends strongly on lattice temperature and impurity concentration.

The spontaneous symmetry breaking should strongly influence the transport effects in bipolar samples, when the transverse fields created by the electrons act on the holes.

Furthermore, an analogue in real space of k-space symmetry breaking may be obtained in suitable MBE structures.

I-3 Nonequilibrium Effects in Quasi-One Dimensional Weak and Strong Localization Regime, Toshiaki Ikoma, *Institute of Industrial Science, University of Tokyo.* The electron transport in ultra-small semiconductor structures has attracted much attention, since quantum interference effect (QIE) of electron waves has potential to realize a new class of electron devices. We have systematically studied the QIEs of electron waves in quasi-one-dimensional AlGaAs/GaAs quantum wires in weak and strong localization regime.

Quasi-one dimensional quantum wires were defined by focused ion beam implantation into selectively doped AlGaAs/GaAs heterojunctions. The electron density is precisely controlled by the gate electric field.

First, we studied the hot electron effect on the weak localization phenomena. The phase coherence length of electron waves estimated from the negative magnetoresistance spectra measured at 0.3 K was found to decrease with increasing input power, which is explained by the increasing inelastic scattering rate due to the rise in electron temperature.

Furthermore, we studied the electron transport in the strong localization regime. We found an anomalous peak in transconductance (g_m) just above the threshold voltage. This peak in g_m collapsed with increasing electric field. In the same region, the drain current exhibited a strong nonlinear behavior when the drain field F_D was low, but became more and more ohmic with increasing F_D. These effects are explained by the electron delocalization due to hot electron effect.

Detailed discussion will be made at the Conference.

I-4 Femtosecond excitations in modulation-doped quantum wells, Wayne H. Knox, *AT&T Bell Laboratories, Holmdel, NJ.* Modulation-doped quantum wells introduce a new parameter into studies of the nonlinear optical response of quantum wells. By selective doping, we can obtain excess electrons or excess holes in the quantum wells with negligible impurity scattering and study the effects on the femtosecond nonlinear optical response. We find that modulation doping causes large changes in the bandedge dynamics in both carrier-carrier scattering rates and the behavior of the gap renormalization. These results are illustrated with a video presentation in which time is expanded by a factor of 10^{14} (i.e., 10 fs/sec). This format allows one to easily see the effects of nonthermal carrier generation and subsequent thermalization and the separate effects of renormalization. These results call for significant new theoretical works, with questions like:

a) Is renormalization instantaneous? Is it uniform in energy?

b) What is the renormalization due to an arbitrary carrier distribution function in two dimensions?

c) What exactly happens to carrier-carrier scattering in the dense Fermi sea of electrons or holes?

d) Can carriers thermalize in times shorter than the inverse plasma frequency?

e) How exactly can we determine carrier distributions from optical signals? What is the nonlinear response of continuum resonances compared to excitons?

I-5 Picosecond relaxation in quantum well systems, John Ryan, *Oxford.*

I-6 Nonequilibrium carrier noise and its effects in microstructures, V. L. Gurevich, *Ioffe Physico-technical Institute, Leningrad.* Noise of nonequilibrium carriers confined to a limited volume is discussed. Both low- and high-frequency noise of classical as well as quantum mechanical origin is considered.

Low-frequency noise of a current-carrying electron gas may be produced by transitions in deep electron traps existing in semiconductors as well as by transitions of atoms (or groups of atoms) between two equilibrium positions. At low temperatures these are tunnel transitions while at higher temperatures they are activated.

Classical high-frequency noise is closely connected with the heating of an electron gas, e.g., by electric field.

Sources of quantum mechanical noise are discussed; their intensity is compared with that of classical noise.

I-7 Nonequilibrium Green's function techniques applied to hot electron quantum transport, Antti-Pekka Jauho, *University of Copenhagen.* During the last few years considerable effort has been devoted to deriving quantum transport equations for semiconductors under extreme conditions (high electric fields, spatial quantization in one or two directions. Here we review the results obtained with nonequilibrium Green function techniques as formulated by Baym and Kadanoff, or by Keldysh. In particular, the following topics will be discussed: (i) Systematic approaches to reduce the transport equation governing the correlation function to a transport equation for the Wigner function; (ii) Limits of validity of the Boltzmann equation; (iii) Recent progress in extending the formalism to inhomogeneous systems; (iv) Numerical results for model semiconductors; and (v) Nonequilibrium screening.

I-8 Hot electrons in resonant-tunneling diodes,* E. R. Brown, *Lincoln Laboratory, MIT.* Recent progress in the area of high-speed resonant-tunneling diodes will be summarized with emphasis on the role played by hot electrons in the transport process. An analysis of the electrostatic and dc current-voltage behavior of double-barrier diodes biased into the negative differential resistance region has been performed. It indicates that the longitudinal kinetic energy of electrons incident on the structure is considerably higher than either kT or the Fermi energy in the neutral region on the cathode side. This is caused by the strong spatial quantization that occurs in the accumulation region contiguous to the outermost heterojunction. The kinetic energy of electrons injected into the depletion layer on the anode side is even higher. The depletion-layer injection energy in our fastest diodes is about 0.2 eV, which corresponds to a theoretical group velocity of 7×10^7 cm/s in $In_{0.53}Ga_{0.47}As$. Our highest oscillation frequency to date, 420 GHz, supports the existence of hot-electron injection because an average drift velocity of at least 4×10^7 cm/s across 80 nm of depleted GaAs must be assumed to explain our data. It is clear that hot-electron phenomena are important to the high-speed performance of resonant-tunneling diodes.

* The speaker acknowledges an ongoing collaboration with T. C. L. G. Sollner, C. D. Parker, W. D. Goodhue, A. R. Calawa and M. J. Manfra, and invaluable support from R. A. Murphy and A. L. McWhorter.
This work was supported by the Air Force Office of Scientific Research, the U. S. Army Research Office, and NASA.

I-9 Dynamics of moving space charge domains in Ge at liquid He temperatures, R. M. Westervelt, A. Kahn, and D. Mar, *Harvard University.* Impact ionization of shallow acceptors in "ultrapure" p-type Ge at liquid He temperatures produces an impurity discharge in samples with ion-implanted p^+ reservoir contacts. The dynamics of the ionization process results in traveling high electric field domains produced by trapped space charge. We present space- and time-resolved experimental measurements of domain motion obtained using a capacitive pickup technique. These results are used to illustrate the different types of domain motion which occur, including both a periodic traversing of the sample as well as more complex types of periodic and chaotic motion typical of nonlinear dynamical systems.

I-10 Space charge currents, domains and instabilities viewed with voltage contrast microscopy, George N. Maracas, *Arizona State University Center for Solid State Electronics Research.* This talk will describe our experimental work on conduction mechanisms in semi-insulating GaAs. The phenomenon of low frequency current oscillations is studied by electrical and optical techniques. The temperature and electric field behavior of the current oscillations exhibit more than one route to chaos in the negative differential resistance region at low electric fields. At high electric fields as the conduction becomes predominantly space charge limited, the material is in the seemingly chaotic regime. We have identified the origin of high frequency terms in the Fourier spectrum of the current waveforms as a function of electric field. They are caused by interactions of the moving deep level domain charge and the cellular *dislocation structure* in the undoped semi-insulating GaAs substrate. This interaction is imaged in real time by observing the surface potential by using a scanning electron microscope in the voltage contrast mode of operation. Details of these measurements and the behavior of the domain charge in different structures are described from the perspective of chaos in GaAs.

I-11 From hot electron transport theory to macroscopic nonlinear and chaotic behavior by impact ionization in semiconductors, E. Schöll, *Institut für Theoretische Physik, Aachen.* The status of our theoretical understanding of self-generated nonlinear and chaotic oscillations in semiconductors associated with impact ionization of impurity centers is reviewed. A full understanding would require the derivation of a macroscopic nonlinear dynamic system exhibiting such behavior from the microscopic level of elementary transport processes. While this is not yet available, there exist attempts to identify the relevant physical mechanisms at different levels of hot electron transport theory [1]. We discuss physical models which give rise to local and global bifurcations of limit cycle oscillations, period-doubling routes to chaos, Farey-tree ordering of mode-locking structures and quasiperiodicity, and bifurcation of traveling waves. Of particular current interest is the modelling of nonlinear spatio-temporal dynamics such as "breathing" current filaments.

[1.] E. Schöll: Nonequilibrium Phase Transitions in Semiconductors (Springer, 1987).

I-12 Electron energy spectroscopy, spatial distributions, and the observation of ballistic transport of hot electrons in the plane of a 2DEG, A. Palevski, U. Sivan, M. Heiblum, and C. P. Umbach, *Yorktown Heights.*

I-13 Nonequilibrium electron dynamics in small semiconductor structures, A. F. J. Levi,* *AT&T Bell Laboratories.* Reducing length scales in n-p-n heterojunction bipolar transistors leads to changes in both the mode of operation and the fundamental limits to device performance [1]. Very high speed 250GHz devices which utilize nonequilibrium electron transport have been demonstrated [2] and we have shown experimentally that ballistic electron motion dominates base and collector transport when device base and collector thicknesses are similar to the mean free path of charge carriers [3,4]. Clearly it is important to understand qualitative changes in the physics of device operation when dimensions are comparable to a mean free path and coherent electron transport between emitter and subcollector contact is possible. In this situation, local equilibrium concepts such as diffusive transport become invalid and we must consider the combined effects of dissipation and elastic scattering from the conduction band profile. For example, in a problem involving both elastic and inelastic scattering channels one has to ensure correct normalization of the particle wave function. If the probability of finding the particle in the initial state is unity then, after interaction, the sum over all possible final state probabilities must also be unity. This unitarity condition leads directly to a feedback mechanism by which inelastic scattering processes influence the probability of elastic scattering. Clearly this feedback mechanism, which is beyond the scope of simple perturbation theory, could be of importance in the design of very small device structures. Recently we have undertaken an experimental and theoretical study of these effects [5]. Both our experimental and theoretical results highlight the need to understand the coherent nonequilibrium electron transport used in an emerging new generation of ultra high speed devices.

[1] Electronics Lett. **24**, 1273 (1988).
[2] Presented at Picosecond Electronics and Optoelectronics Conference, Salt Lake City, Utah, 1989.
[3] Appl. Phys. Lett. **52**, 2247 (1988).
[4] Appl. Phys. Lett. **54**, 813 (1989).
[5] Phys. Rev. Lett. **62**, 1683 (1989) and unpublished.

* In collaboration with K. Berthold, S. Schmitt-Rink, A. Pinczuk, R. N. Nottenburg, Y. K. Chen, M. B. Panish, L. N. Pfeiffer, and J. Cunningham.

I-14 Femtosecond processes in semiconductors, Jagdeep Shah, *AT&T Bell Labs, Holmdel, NJ, USA.* This talk will review a number of milestones in the 20 year history of optical investigation of hot carriers in semiconductors and then discuss a number of recent results, including (1) studies of carrier relaxation using 6 femtosecond pulses and (2) studies of tunneling in semiconductor microstructures using ultrafast optical techniques.

I-15 Monte Carlo simulation of hot-carrier transport in *real* semiconductor devices, M. V. Fischetti, S. E. Laux, D. Ahn, and D. J. Frank, *IBM T. J. Watson Res. Ctr., Yorktown Heights.* We shall present results of our simulation of hot-carrier transport in Si and GaAs semiconductor devices. The major new features of the Monte Carlo model we have used are:

1. The semiconductor is modeled beyond the effective-mass approximation using the band structure obtained from empirical-pseudopotential calculations.
2. The carrier-phonon, carrier-impurity, and carrier-carrier scattering rates are computed in a way consistent with the full band-structure of the solid.
3. The long-range carrier-carrier interaction and space-charge effects are included by coupling the Monte Carlo simulation to a self-consistent 2-dimensional Poisson solution updated at a frequency large enough to resolve the plasma oscillations in highly-doped regions. This, together with an approximate implementation of degeneracy effects, make it possible to simulate devices with contact regions with realistically heavy doping.

Three different sets of devices have been studied, each highlighting a different feature of the models employed:
1. In experimental submicron n-channel and p-channel Si MOSFETs (with channel lengths as small as 60 nm) velocity overshoot and highly nonlocal, off-equilibrium phenomena have been observed. In these ultra-small structures, the inclusion of the full band-structure of the crystal is an essential ingredient, since it has the effect of reducing the amount of velocity overshoot via electron transfer to upper conduction valleys, particularly at large biases and low temperatures.
2. In Si p-n-p and n-p-n bipolar transistors with base widths well below 50 nm, the off-equilibrium characteristics of transport and the self-consistent coupling of the Monte Carlo model to the Poisson solver are absolutely necessary in order to understand the behavior of the devices. The carrier-carrier interaction also plays a major role in the thermalization of the hot carriers in the highly doped collector region.
3. In submicron GaAs MESFETs (gate lengths down to 0.15 μm), band-structure effects appear to dominate the hot-carrier transport, while the comparison between experimental and simulated current-voltage characteristics is hampered by the difficulty of knowing the doping profile in the device. Finally, we shall discuss the importance of including quantization effects (i.e., subbands in inversion layers and quantum wells) by solving the Luttinger-Slater equation with the "exact", i.e., non-parabolic) carrier dispersion.

I-16 Experimental study of hot carriers in small size Si-MOSFETs, A. Toriumi, *Toshiba Corp. ULSI Res. Ctr.* Experimental study of hot carrier effects in Si MOSFETs is reviewed and it is shown that the deeper investigation is quite important in developing the actual VLSIs. In this decade, a lot of work has been done empirically from the viewpoint of "hot carrier reliability in MOSFETs," where the emphasis is placed primarily on the physics in the oxide or at the Si/SiO2 interface. This paper will emphasize recent experimental results, directly related to the hot electron energy such as photoemission from MOSFET or velocity overshoot in ultra small MOSFETs. And, I will also discuss some of many efforts to overcome the actual reliability problems caused by hot electrons we are confronted with.

MB-1 Intersubband emission from superlattices, M. Helm, P. England, E. Colas, F. DeRosa, and S.J. Allen, Jr., *Bellcore, Red Bank, N.J. 07701-7040, USA.* We report the first observation of light emission from transitions between subbands in quantum wells or superlattices. The samples used were superlattices with rather wide wells (300 - 400 Å), ensuring that several subbands lie below the optical phonon energy. This choice reduces the nonradiative relaxation rate of the electrons in the lower subbands, and herewith increases the quantum efficiency for light emission. Two methods of exciting the electrons into higher subbands are employed: (1) Heating of the electrons in an electric field parallel to the layers [1] and (2) Electron injection perpendicular to the layers, i.e. sequential resonant tunneling.

Since the radiation generated is polarized perpendicular to the layers, a metallic grating is used to couple the emitted light out of the surface. The emission spectrum is analyzed with a broadband detector and a tunable InSb cyclotron resonance filter. In the sequential resonant tunneling experiment, we observe emission from the three lowest intersubband transitions. The relative strength of the lines enables us to obtain information about the hot electron distribution. An intersubband electron temperature as high as 120 K (at a lattice temperature of 20 K) can be deduced. We also discuss possibilities to achieve population inversion between subbands.

[1] M. Helm *et al.*, Appl. Phys. Lett. **53**, 1714 (1988).

MP-1 Far-infrared radiation induced photovoltage of inversion electrons on GaAs, F. Thiele, E. Batke, J. P. Kotthaus, V. Dolgopolov,* *Institut für Angewandte Physik, D-2000 Hamburg,* G. Weimann,+ W. Schlapp, *Forschungsinstitut der Deutschen Bundespost, D-6100 Darmstadt. (* Permanent address: Institute of Solid State Physics, Chernogolovka, USSR; + also at Walter-Schottky-Institut, D-8000 München.)* In gated GaAs-AlAs heterojunctions the gate potential can be significantly changed if the device absorbs far-infrared (FIR) radiation of sufficient intensity. Here we investigate a novel photovoltaic response occurring in GaAs heterojunctions whenever radiation of a FIR molecular laser is absorbed at cyclotron resonance by inversion electrons. With FIR laser intensities in the regime of mW/cm^2 photovoltages up to several mV can be observed at cyclotron resonance. The dependence of this photovoltaic response on electron density N_s, magnetic field strength B and laser intensity is studied in detail. We find the sign and the magnitude of the photosignal to strongly depend on the Landau-level filling factor $v=hN_s/eB$ with strongest signals around even filling factors. Our experiment can be understood within the framework of carrier heating due to the absorbed FIR radiation. We present a simple model demonstrating that the photovoltage reflects the difference in the chemical potential of the inversion electrons at two slightly different temperatures. For a quantitative description of the photovoltage we have to include a finite Landau-level width as well as a finite density of states between the Landau-levels. Our analysis indicates a rise of the electron temperature up to 10K above the lattice temperature of ≤4.2K under FIR illumination. To support our analysis we performed Shubnikov-de Haas experiments with and without FIR illumination and independently estimate an increase of the electron temperature of about 10K consistent with our analysis of the photovoltage. Our experiment demonstrates a sensitive method to verify the chemical potential of space-charge layers and provides a possibility to study the density of states. A possible technical application of gated heterojunctions as fast FIR detectors will be discussed.

MP-2 Tunable cyclotron-resonance laser based on hot holes in germanium applied to FIR-spectroscopy of GaAs heterostructures, K. Unterrainer, C. Kremser, E. Gornik, *Institute of Experimental Physics, A-6U20 Innsbruck, Austria,* Yu.L. Ivanov, *Ioffe Institute, Leningrad, USSR.* An inversion within the Landau levels of the light hole band of germanium is possible in crossed electric and magnetic fields when a few Landau levels lie below the optical phonon energy and the higher Landau levels are influenced by the optical phonons. In such a situation the interplay between acoustical and optical scattering processes causes an inversion between Landau levels [1] which is enhanced by tunneling of holes from the heavy hole band [2]. Stimulated cyclotron-resonance emission [3] has been observed already for wavelengths > 200 micron in samples with a carrier concentration of $N_A\text{-}N_D = 8\times10^{12}\ cm^{-3}$.

We have observed stimulated cyclotron—resonance emission from samples with a concentration $N_A\text{-}N_D = 5\times10^{13}\ cm^{-3}$. The emission is analyzed both with a broadband Ge-detector and a narrow band magnetic field tunable GaAs detector (resolution 0.2 cm^{-1}). The spectrum consists of a single line which is linearly tunable by the magnetic field in a range between 50 cm^{-1} and 80 cm^{-1}. The linewidth is about 0.4 cm^{-1}. The corresponding cyclotron mass is higher than the cyclotron mass determined from spontaneous emission experiments which gives evidence that the inversion takes places between higher Landau levels.

High resolution spectroscopy is demonstrated for the first time: FIR transmission spectra of a GaAs heterostructure are measured as a function of the applied magnetic field. The tunability of the cyclotron resonance laser enables the study of the cyclotron resonance linewidth. The linewidth response of the same sample is also investigated.

[1] M. Helm, E. Gornik, Phys. Rev. **34**, 7459 (1986).
[2] M.I. Dyakonov, V.I. Perel, Sov. Phys. JETP *65*, 200 (1987).
[3] Yu.B. Vasilyev, Yu.L. Ivanov, in "Proc. of the 18th Int. Conf. on the Physics of Semiconductors, Stockholm, 1987", Ed. 0. Engstrom (World Scientific Publishing, Singapore, 1987) p.1659.

MP-3 FIR NDC under hot electron intervalley transfer, Alexander Andronov and Igor Nefedov, *Institute of Applied Physics of the Academy of Sciences, Gorky, USSR.* Since Fawcett and Rees's 1969 work, it is well known that under hot electron intervalley transfer in GaAs and related compounds at an electric field $E \gg E_{th}$, E_{th} is the Gunn effect threshold, the low (Γ) valley population inversion takes place. However, all attempts to utilize this inversion in FIR NDC have failed so far because there is no pronounced resonance in the hot electron system here.

By application of a magnetic field **H**ǁ**E**, CR is introduced and the inversion is turned into the Landau level population inversion. As a result at high enough **H** the inhomogeneous broadening of the CR line (produced by Γ-valley nonparabolicity) separates contributions to transverse differential conductivity (TDC) of the inverted and equilibrium-like parts of Γ-valley distribution and CR NDC arises.

The report gives a simplified analysis in the framework of Γ-X model and τ-approximation calculations of TDC and a thorough discussion (based on direct Monte-Carlo simulations of TDC) of the conditions for CR NDC, value of the corresponding FIR amplification coefficient, etc. It also presents calculations of the electric field profiles in planar n-GaAs structures (similar to those used in travelling wave FET's) for which this CR NDC can be realized.

Another possibility for FIR NDC under hot electron intervalley transfer is the case of lateral transport of multiwell heterostructure with a parabolically graded bottom of the wells. The oscillation frequency of an electron in the wells similar to the cyclotron frequency in **H**ǁ**E** determines the FIR NDC band here. The report discusses the results of analytical calculation and computer simulation of electron distribution and TDC at E » E_{th} here.

MP-4 Frequency range and distributions of inverted hot hole generated FIR in germanium, V. I. Gavrilenko, N. G. Kalugin, Z. F. Krasil'nik, and V. V. Nikonorov, *Gorky.*

MP-5 Smith-Purcell-emission from a drifting 2D-carrier gas in GaAs, E. Gornik, *Walter Schottky Institut (TU München), Am Coulombwall, D-8046 Garching,* D. Weiss, *Max Planck Institut für Festkörperphysik, Stuttgart, FRG,* G. Wolff, G. Weimann, *Walter Schottky Institut ,* R. Christanell, W. Beinstingl, *Institut für Experimentalphysik, Innsbruck, Austria.* A direct measurement of the distribution function in high electric fields would enable a precise determination of carrier relaxation processes. One step in this direction is the application of the Smith-Purcell effect [1] to the 2D carrier system: the introduction of a periodic potential of period l induces an energy loss in a drifting carrier gas via photon emission. The angle between the drift and the grating momentum is varied by using different sample geometries. The geometry—dependent emission spectra are monitored through a magnetic-field—tuned InSb—detector [2].

We have performed a systematic study of the drift velocity for a series of GaAs/GaAlAs heterostructures with zero field mobilities at 4.2 K ranging from 10^5 to 10^6 cm^2/Vs in the temperature range between 4.2 K and 300 K.

The electron temperature at 4.2 K was obtained for low mobility samples, from broadband hot electron emission experiments [3], for high mobility samples the Smith-Purcell effect was used [4]. The experimentally derived mobilities and electron temperatures were compared with a theory developed by Lei and Ting [5]. The agreement for the mobility and the electron temperature is excellent: we find that for the high mobility samples the electron heating is considerably weaker since energy is stored in the drift of the carrier gas. However, the derived electron temperatures do not reveal a meaningful correlation between electron temperature and energy loss rate.

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MC-1 Hot electron transport in high-lying minibands in semiconductor superlattices, P. England, J. R. Hayes, E. Colas and M. Helm, *Bellcore, Red Bank.* We describe measurements on GaAs/AlGaAs hot electron transistor structures with a superlattice in the base region. The emitter, or electron injector, is a tunnel barrier and the collector is a triangle barrier electron spectrometer. The base contains typically 6 periods of superlattice. We have studied both strongly coupled superlattices where substantial miniband conduction is seen, and structures in which we intentionally preclude the possibility of miniband conduction. By appropriately biasing the electron injector, we can inject hot carriers at arbitrary energy into the superlattice miniband structure. The tunneling characteristic of this junction reflects directly the miniband density-of-states. Simultaneously, we may analyze the electron distribution function after traversing the superlattice using the electron spectrometer. We find that for the strongly coupled superlattices, when biased to inject into a given miniband (the second, third or fourth), a well resolved peak appears in the analyzer electron distribution, whose position is almost independent of injection energy (within a given band) indicating significant band conduction in high-lying minibands. We have also studied the fraction of electrons that traverse the superlattice quasi-ballistically as a function of injection energy. We find that with the spectrometer set to collect electrons in a given band, when we bias to inject into that band, the fraction of electrons which traverse the superlattice ballistically rises by typically 2 to 3 orders of magnitude for a very small increase in the injection energy. We have been able to successfully model quantitatively the behavior of the transfer function by assuming the electron transport is governed by a tight-binding miniband density of states, together with scattering out of the band. These measurements represent the first observation of hot electrons in high-lying minibands in superlattices, and give us important information on electron dynamics in these systems.

MC-2 High-field transport and NDR with hot phonons in degenerate semiconductors, R. Gupta and B. K. Ridley, *University of Essex, Colchester, United Kingdom.* The effect of phonons in non-thermodynamic equilibrium (hot-phonons) on steady-state transport is studied in degenerate bulk and two-dimensional semiconductor structures. The model assumes a single parabolic band with scattering confined to polar optic modes, restricted to interface modes in the 2D case. Also a constant phonon lifetime of 7 ps is assumed and the Cerenkov-effects are taken to be negligible. Hot phonons lead to a saturation of the drift velocity at high electric fields, for both the 3D and the 2D degenerate systems. For the latter, the value of the saturation drift velocity increases with increasing width (L) of the quantum-well (as in the non-degenerate case) and also with increasing 2D carrier density (unlike the non-degenerate case). In addition, hot phonons coupled to degenerate electrons lead to an NDR in both the 3D and the 2D semiconducting systems at high doping densities, e.g., $n=4\times10^{18}$ cm^{-3} in bulk GaAs and $n=2.5\times10^{12}$ cm^{-2} in GaAs quantum-well with L=50 Å. This is contrary to the case of nondegenerate and weakly degenerate systems where hot phonons tend to quench inter-valley and real-space transfer NDR.

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MC-3 Magneto-phonon resonances in the effective temperature of photo-excited carriers in GaAs/(Ga,Al)As quantum wells, H. A. J. M. Reinen, T. T. J. M. Berendschot, P. C. M. Christianen, H. J. A. Bluyssen, *Research Institute for Materials and High Field Magnet Laboratory, University of Nijmegen, The Netherlands,* H. P. Meier, *I.B.M. Research Laboratories, Rüschlikon, Switzerland.* Hot-electron magnetophonon resonance (HEMPR), in which the emission of optic phonons allows electrons to transfer from higher to lower Landau levels, has been extensively used in the study of carrier-phonon interactions in semiconductor systems. HEMPR has been exclusively studied using transport measurements, demanding the use of modulation-doped samples in order to provide carriers in the layer of interest. However, in this paper we demonstrate for the first time that HEMPR can also be observed in the effective temperature of optically-excited 2D carriers, thus allowing both doped and undoped GaAs/(Ga,Al)As quantum wells and structures to be studied.

We have analysed the photoluminescence spectra from both modulation-doped and undoped GaAs-(Ga,Al)As quantum wells taken in magnetic fields up to 25 T using constant optical excitation intensity, and deduced the carrier temperature, density and Landau level widths as a function of magnetic field. For high excitation intensities, the effective electron temperature in all samples shows a large increase with field up to 20 T, and a subsequent decrease to 24T: this oscillatory behaviour is due to HEMPR.

In order to support this suggestion we have derived a model for the rate of energy loss of a 2D electron due to interactions with phonons in high magnetic fields, and used this to calculate the electron temperature as a function of magnetic field from the equilibrium condition that the carrier energy loss rate due to LO phonon emission is equal to the energy input rate. In all cases non-equilibrium phonon effects and conduction band non-parabolicity are taken into account. The energy input rate i. our experiments is calculated at 15 T using the model and the experimentally-observed values for the electron temperature, electron density and Landau level widths: for other values of the magnetic field the same energy input rate is assumed, and the electron temperature derived using the model. Good agreement with the experimental results from both doped and undoped quantum wells and for all excitation densities is obtained at high magnetic field with the use of no adjustable parameters, demonstrating that the observed carrier temperature oscillations are indeed due to HEMPR.

MC-4 The one-dimensional quantized ballistic resistance in GaAs/AlGaAs heterojunctions with varying experimental conditions, R. J. Brown, M. J. Kelly*, R. Newbury, M. Pepper, D. G. Hasko, H. Ahmed, D. C. Peacock*, D. A. Ritchie, J.E.F. Frost and G. A. C. Jones, *Cavendish Laboratory, Cambridge, England.* We present results obtained from experimental observations on a series of "split gate" MESFET's where the gates define a narrow constriction in the two dimensional electron gas (2DEG) formed by a GaAs/AlGaAs heterostructure. The gates of varying dimensions were fabricated using electron beam lithography and lift-off of gold/palladium. The properties of these devices have been investigated over a temperature range of 4.2K to less than 100mK. The effects of various magnitudes of magnetic fields have also been studied.

The effect of introducing a ballistic channel into a 2DEG is known to produce one-dimensional subbands [1], giving a sample resistance of $h/(2e^2i)$ where i is in the number of occupied subband [2,3,4] when the sample length is less than the scattering mean free path of the sample. As each subband is removed this causes the resistance of the device to increase by a discrete amount, due to i changing by one, and then to remain close to that resistance until the channel width is reduced by such an extent that the next subband can no longer conduct.

Many theoretical papers [5,6,7,8] have recently been written predicting the effects of changing the various available parameters on the degree of quantization. For example, the size and shape of the constriction, temperature, etc. These results comprise the first systematic experimental study of the quantization as a function of the various parameters mentioned.

Our experiments reveal several interesting trends which we relate directly to theoretical predictions. We show how the sharpness of the quantization is greatly reduced and eventually smoothed out completely as the temperature is increased. As the channel length is increased one observes repeatable structure which may be attributable to universal conductance fluctuations introduced as the elastic scattering length decreases.

We also demonstrate the possible observation of resonances at resistances above that corresponding to only one 1D subband being occupied. The role of electron heating on the plateaux definition will be reported and discussed.

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MC-5 Non-linearity and intersubband population inversion in quantum wire structures, S. Briggs, D. Jovanovic, and J.P. Leburton, *University of Illinois at Urbana-Champaign.* With the continuous advance in fine line lithography, the field of one-dimensional (1D) systems has been growing rapidly for several years. Although interest in these systems has focused primarily on quantum interference and localization phenomena, it is anticipated that the technological obstacles to strong confinement will soon be overcome and 1D effects will be observable above 4 K. Because of the absence of angular randomization during scattering in 1D systems the carrier distribution is sensitive to external perturbations and deviates from the equilibrium relatively rapidly. In this paper we investigate the influence of phonon scattering in multi-subband quantum wire structures and focus particularly on the onset of non-linearity using a Monte Carlo simulation. Electron transport is non-linear for fields as low as 50 V/cm with large deviations from 3 Maxwellian distribution even at room temperature.

In addition, when the spacing between subbands in a quantum wire is equal to the optic phonon energy a situation occurs under longitudinal field conditions where the upper subband population is enhanced with respect to the lower subband. In the case where a third, intermediate sub-band is located slightly below the upper subband we obtain a population inversion between the upper and intermediate subband. We calculate intersubband optical transitions for various confinement geometries. The possibility of far-infrared stimulated emission seems to be significant.

MP-6 *Strong electric field effect on weak localization,* G. Y. Hu and R. F. O'Connell, *Department of Physics and Astronomy, Louisiana State University, Baton Rouge, LA 70803-4001 USA.* The influence of an electric field on weak localization is studied by a recently proposed generalized quantum Langevin equation approach to the conductivity problem. A general formula for the memory function of the non-interacting electron gas, in the presence of high order impurity scattering and an arbitrary electric field, is derived. In the low-field case, a scale- and frequency-dependent conductivity is obtained, which reduces to the well known scale-dependent conductivity in the static limit. In the high-field case, the conductivity is field-dependent through the drift velocity. It is shown that the presence of strong electric fields tends to delocalize the one- and two-dimensional electron systems if one adopts the electron heating model. However, if the electron gas does not heat up, the conductivity will be field-independent.

MP-7 Spatial anisotropy of the phonon emission by a hot two-dimensional electron gas in a GaAs/AlGaAs heterojunction, P. Hawker, A. J. Kent, O. H. Hughes, and L. J. Challis, *University of Nottingham, Nottingham, U.K.* The primary energy relaxation process for hot 2-D electrons in semiconductor devices is through the emission of phonons. In GaAs/AlGaAs heterojunctions the phonon emission is believed to consist mainly of acoustic modes at electron temperatures below about 50K, while at higher temperatures optic phonon emission dominates. There has been considerable theoretical interest in these electron-phonon processes with the aim of understanding the temperature and field dependence of the electron mobility in modulation doped heterostructures and significant progress has been made. Experimental investigations have in the main been confined to transport measurements, direct studies of the phonon emission are rare due to difficulties in obtaining sufficiently good ohmic contacts.

We have used phonon imaging techniques to investigate the spatial anisotropy of the phonon emission from a small area (0.3×0.3 nn^2) of two-dimensional electron gas (2DEG) in GaAs/AlGaAs heterojunction. The 2DEG was heated by applying electrical pulses of duration 100 ns and typical peak power 100 mW. The 2DEG had a sheet concentration of 0.5×10^{12} cm^{-2} and a 4.2K mobility of 130000 cm^2/V-sec.

Line scans of the phonon intensity as a function of angle between the phonon propagation direction and the normal to the plane of the 2DEG have been obtained. Our results allow the phonon emission to be attributed directly to the 2DEG and not the ohmic contact regions. We find that the phonon emission is concentrated within a cone of semi-angle 50 degrees to the normal to the 2DEG and that in applied magnetic fields of up to 7T, the emission is pushed still closer to the normal. These results are shown to be consistent with the theory of 2-D electron-phonon interactions, assuming that a significant proportion of the emissions is into acoustic modes.

MP-8 Enhancement of energy relaxation rates in semiconductor superlattices, M.P. Chamberlain and M. Babiker, *University of Essex, Colchester, U.K.* Energy relaxation of hot electrons is a subject of considerable importance for all microstructures based upon multiple quantum wells. In a superlattice, hot carriers, created e.g. by photoexcitation or by electrical injection, initially occupy so-called delocalised states which have energies that lie above the barrier energy of the superlattice and correspond to motion perpendicular to the layers. In superlattices based on polar materials such carriers relax energy primarily by emission of LO phonons.

This work concentrates on calculating the rate of LO-phonon-mediated transitions in a superlattice at low electron densities using a bulk phonon model but including the effect of the superlattice on the electrons. We have calculated transition rates between adjacent energy subbands within the well and also above the barrier energy, varying well width d_2 in a $Ga_{0.7}Al_{0.3}As$/GaAs superlattice with fixed GaAlAs thickness $d_1=100$Å. *Using typical parameters,* we demonstrate that a significant enhancement of the transition rate from the bottom of the first excited subband to the ground state subband is achieved for well widths approaching 180Å. The enhanced rate occurs at the well width when the energy separation between the first two electron subbands is of the order of the phonon quantum of energy $\hbar\omega_L$. As a result of energy and momentum conservation the value of the in-plane phonon momentum, $K_{\|}$, is zero at this particular energy level separation leading to a maximum in the transition rate. These features have also been exhibited in calculations involving transitions between higher pairs of energy subbands. We include results for transitions between the third and second electron subbands where the electron states are above the barrier energy. The rate for this transition shows an enhancement for well widths 35Å. Work now in progress seeks to establish whether, and in what manner, screening and phonon confinement effects are likely to modify transition rates in the region of well widths exhibiting the marked enhancement discussed here.

MP-9 Inelastic scattering effects on carrier relaxation in quantum-well-based hot electron structures,* R. Jalabert and S. Das Sarma, *University of Maryland, College Park.* The mean free path of hot electrons traversing high quality GaAs-based microstructures is essentially determined by inelastic scattering events[1]. In this work we study the inelastic (phase breaking) scattering time of quasi-two-dimensional carriers with energies significantly above the Fermi energy. Coulomb electron-electron and Fröhlich electron-LO-phonon interactions are treated on equal footing, which gives rise to damping by the excitation of electron-hole pairs or the emission of coupled plasmon-phonon modes. The inelastic scattering times obtained are comparable to the transit times of the hot electrons indicating the importance of the inelastic processes. Our results are highly dependent on the electron density in the transit region indicating the importance of charge build up and doping. The geometrical confinement of the LO-phonons (slab modes) is shown to have important quantitative effects on the inelastic mean free path for very thin microstructures and at low electron densities. We will present detailed theoretical results for the inelastic mean free paths as a function of electron energy and electron density in the system.

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MP-10 "Electron-electron scattering in AlGaAs/GaAs 2DEG systems under hot-electron conditions, A. H. Guerrero, *U.S. Army Electronics Technology and Devices Laboratory, Fort Monmouth.* A molecular dynamics approach is combined with the Monte Carlo simulation technique to model electron transport parallel to a AlGaAs/GaAs interface. The model includes remote impurity scattering and electron-electron (e-e) scattering. The screening of the Coulomb interaction is allowed to evolve dynamically, and the spatial localization of the 2 dimensional electrons near the heterojunction is determined by the self-consistent fields. The scattering rates for the electron-phonon interaction are based on 2 dimensional density of states for electrons located near the interface.

For single heterostructure devices i.e. a HEMT, experimental results indicate that the very high mobilities which occur at low applied fields rapidly degenerate at higher fields, and that the electron drift velocity saturates. A saturation of the drift velocity is not predicted by Monte-Carlo studies which do not include e-e scattering; these numerical investigations are more in accord with experimental measurements performed on multiple heterojunction devices (quantum well structures), which show significant negative differential conductivity (ndc) in the electron steady state drift velocity vs. field (V-E) characteristics.

In a system of hot electrons confined near a single interface a significant fraction of the electrons populate the subsidiary conduction band valleys. In the subsidiary valleys the electrons behave as 3 dimensional electrons, rather than as 2D electrons. The diffusion of electrons away from the interface, a process which does not occur in quantum well devices (except in the form of real-space transfer) disturbs the balance which usually exists between the 2D and 3.D electron populations in the steady state. Electrons in the GaAs substrate will also be coupled to the .2DEG system, complicating the features of the transport significantly. This numerical study indicates that the electron sheet density near a heterojunction plays an important role in determining the transport properties of 2D systems; in particular the density of heavy (3D) electrons affects the magnitude of the ndc which is observed in confined structures. The results indicate the importance of electron-electron scattering in 2DEG systems.

MP-11 Real space transfer rates for polar optical phonon scattering from asymmetric quantum wells, C. S. Lent and Lie Liang, *University of Notre Dame, Indiana.* Electrons in a quantum well can be heated by applying a field parallel to the well walls. Such electrons can gain energy sufficient to escape the well. This real space transfer phenomena has been studied extensively by Hess and others [1,2], and is exploited in the CHINT and NERFET devices of Kastalsky and Luryi [3,4]. Extensive analysis of these structures has been done using semiclassical Monte Carlo techniques. A necessary input to such calculations is the scattering rate from the confined electron states to the free states out of the well. Currently approximations are used which neglect the 2-D to 3-D nature of the transition.

We calculate the rate at which electrons bound in asymmetric semiconductor quantum wells are scattered out of the well by absorption or emission of polar optical phonons. The 2-D to 3-D nature of the scattering is included. The final states after scattering are states which carry current either to the right or left. We find that rates for scattering out of the well can be significantly smaller than bulk scattering rates. We also show that asymmetries in the well shape result in a directional dependence for the final state current. That is, electrons scatter out preferentially to the left or to the right depending on the details of the well potential. Consequences for real space transfer device design are discussed.

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MP-12 Monte Carlo Simulation of Hot Electrons in InAlAs/InGaAs Heterojunctions, E. Kobayashi, T. Matsuoka, K. Taniguchi and C. Hamaguchi, *Osaka University, Japan.* Monte Carlo simulation was carried out to investigate hot electron transport in $In_{0.52}Al_{0.48}As/In_{0.53}Ga_{0.47}As$ at 77K, where scattering processes due to alloy disorder potential and two modes of LO phonons,"GaAs-like" LO phonon and "InAs-like" LO phonon, are taken into account in addition to acoustic deformation potential, ionized impurity, nonpolar optical phonon, and intervalley phonon scatterings. We discuss the importance of the conduction band nonparabolicity. We first solved coupled Schrödinger and Poisson equations self-consistently to obtain electric subbands (6, 4, and 1 subbands in Γ, L, and X valleys, respectively) and wave functions in these subbands, and then calculated the scattering probability in each subband as a function of the electron energy. The coupling constants of electron-LO phonons (two types of LO phonons) are determined from the magnetophonon resonance experiments in bulk InGaAs and the alloy disorder potential is estimated from the analysis of low field mobility. We investigated the effects of the Γ - L valley energy separation and alloy disorder potential on the high field drift velocity. It is found that the alloy disorder scattering reduces the drift velocity, and that the maximum drift velocity and negative differential mobility depend on the energy separation between Γ and L valleys, indicating that the intervalley scattering plays an important role in the hot electron transport in the heterostructures. The maximum drift velocity ranges from 1.8 to 2.7×10^7 cm/s depending on the alloy disorder potential (1.1 to 0.5 eV). The present simulation shows a reasonable agreement with the experimental results. We also investigated the drift velocity overshoot and found that the maximum overshoot velocity is about 6×10^7 cm/s.

MP-13 Geometric effects of scattering in microstructures,* A. M. Kriman, R. P. Joshi, B. S. Haukness and D. K. Ferry, *Arizona State University, Tempe, AZ.* Transfer Matrix techniques are used to study elastic scattering by defects embedded in quasi-one-dimensional microstructures. This makes possible an exact analysis of phenomena that arise from breaking of the transverse translation invariance by real defects. The dependence of scattering cross sections on the position of the scatterer is studied for parallel transport in quantum wells and for perpendicular transport across single and multiple barrier structures. It is found that in laterally confined structures, delta-function and other extremely sharp models of a single defect lead to sharp resonances when such defects are well isolated.

Such features are associated with multiple reflections between the lateral confining potential and the defect potential. In single-barrier structures with a single nearby defect, a scaling behavior is found that relates scattering cross section for defects at different distances to that at a fixed distance with different energy scales. In double-barrier resonant tunneling diodes (DBRTDs), the position of the transmission peak is affected primarily by defects within the quantum well region. The height of the transmission peak is very sensitive to the positions of defects within that region, acting essentially as a probe of the resonance wave function. Defects in front of a DBRTD also affect the valley current by modifying the longitudinal component of the incident momentum. Defects behind a DBRTD have a relatively much smaller effect on the transport properties.

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MP-14 Modulation of impurity scattering rates by wavefunction engineering in quasi-2-D systems and its device applications,* S. Bhobe, W. Porod, and S. Bandyopadhyay, *University of Notre Dame, IN.* In this paper, we investigate the detailed nature of transient hot electron transport in a single, selectively doped GaAs quantum well, where the scattering rates are modulated by wavefunction engineering. The scattering rates are explicit functions of the electronic states in the well which can be altered by a transverse electric field thereby altering the rates. The electronic states are obtained from self-consistent solutions to the coupled system of the Schrödinger and Poisson equations. From these wavefunctions, the scattering rates are calculated for both local and remote impurity scattering. These rates are then used as input to Monte Carlo simulations to model electron transport in the quantum well. This allows us to study the time-dependent decay of momentum of an e mble of hot electrons traveling parallel to the interface.

As an example of 'modulated scattering' we have investigated the momentum relaxation of electrons injected into a well whose right half is doped with impurities. When the wavefunction is skewed away from the selectively doped side by an electric field applied perpendicular to the well interface, the momentum relaxation time, and hence the electronic mobility, increases by several orders of magnitude. Therefore, by skewing the wavefunction towards either side of the well, one can modulate the conductance and thus realize a switching transistor. Such a transistor, termed a 'Velocity Modulation Transistor,' has been proposed as an ultrafast device si 'e its switching time is not limited by the transit ..ne. We perform a detailed analysis of this device with particular emphasis on the transient switching speed.

* This work was supported by the Air Force Office of Scientific Research.

MP-15 Time-of-flight experiments on 2D electron gases, E. A. E. Zwaal, W. T. Gorissen, R. M. Y. Ruber, J. H. Wolter, *Eindhoven University of Technology, Eindhoven, The Netherlands.* In modulation doped GaAs/AlGaAs heterostructures the 2D electron gas is spatially separated from the ionized donors. Due to the reduced impurity scattering very high electron mobilities can be achieved in these structures.

We determined the 2D electron drift mobility by means of measurements of the drift velocity. The experiments were carried out with the help of the time-of-flight technique.

In the experiments excess carriers are created by a short (subnanosecond) laser pulse focused to a line-shaped spot (< 5 micrometer) next to the negative contact made on a rectangular Hall-bar. The drift of the electrons to the positive contact induces a photocurrent in the external circuit. From the width of the photocurrent signal the electron drift velocity can be determined. With inverted polarity the drift velocity of the holes can be measured. The photocurrents are measured by means of a digital sampling scope.

We performed time-of-flight experiments at various electric fields at room temperature. In the electric field dependence of the electron drift velocity we observe a maximum at 2 kV/cm. This is in accordance with Monte Carlo calculations by Yokoyama and Hess [1]. With increasing excitation density we observe a decrease in drift velocity due to space charge effects. The results will be discussed.

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MP-16 Splitting and shift of the hot magneto-phonon resonance peaks, P. Warmenbol*, F.M. Peeters and J.T. Devreese†, *University of Antwerp(UIA), Antwerpen.* The splitting of the magneto-phonon resonance peaks in a two-dimensional electron gas is investigated as function of the electric field (or average electron velocity) for different values of the broadening of the Landau levels. We found that for small broadening the maxima (and minima) in the magneto-phonon resonances are split into two peaks. A new physical interpretation is presented for this splitting which is based on the separate cont· ·tions of LO-phonon absorption and emission processes.

A shift of the whole resonant maxima (and minima) is observed when the broadening of the Landau levels is large.

A new explanation if given for the "apparent" temperature and density dependence of the optical phonon frequency in heterostructures as determined from magneto-phonon resonance experiments [1]. A mechanism is proposed which is able to produce the observed shifts in the resonant position and which is consistent with an interaction with the optical phonon mode of the bulk material.

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MP-17 High field mobility of light holes in strained InGaAs quantum wells,* H. P. Hjalmarson, I. J. Fritz, and L. R. Dawson, *Sandia National Laboratories.* Strained p-doped InGaAs quantum wells with GaAs barriers have potential use in high speed devices. In these structures, hole transport occurs within the in-plane light-hole band separated by $\Delta \sim$ 10-100 meV from the in-plane heavy-hole band. The light mass leads to high mobility at low electric fields. Monte Carlo transport calculations reveal that field heating from the high-mobility, light-hole band to the low-mobility, heavy-hole band can cause negative differential mobility (NDM). These calculations can be qualitatively understood in terms of the strain splitting ~ and the optical phonon energy $\hbar\omega_0 \sim 36$ meV. If $\Delta >> \hbar\omega_0$, NDM occurs, whereas if $\Delta \sim \hbar\omega_0$ the low field mobility is enhanced but NDM is avoided. When scattering from interface roughness is also included, these calculations are consistent with our high field transport data.

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MP-18 Negative differential perpendicular velocity in GaAs/AlAs superlattices, A. Sibille, J;F. Palmier, *CNET, BAGNEUX, France*, F. Mollot *L2M, CNRS, BAGNEUX, France*, and J.C. Esnault. It has recently been demonstrated [1] that the electron velocity-field V(F) relations in perpendicular biased GaAs/AlAs superlattices exhibited a reproducible negative differential velocity (NDV). In properly designed structures this phenomenon leads to negative differential conductance (NDC) observed both under d.c. voltages and at microwave frequencies [2]. Clear evidence has also been presented [1,2] that the superlattice NDV was a bulk superlattice effect, in contrast to most published works where NDC resulted from high field domain formation on individualized periods or localized "quantum defects".

We investigate here the temperature, hydrostatic pressure and superlattice parameter dependence of the high field perpendicular transport in a series of such superlattices. These experiments allow to distinguish between the conduction processes which are specific to the ~ miniband, like Wannier-Stark localisation or miniband nonparabolicity, and those which also involve the indirect X valley (superlattice Gunn transfer). Their relative contribution as a function of the various parameters will be described.

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MP-19 Calculations of Zener interminiband tunneling rates in superlattices, A. Sibille, *CNET, BAGNEUX, France.* ABSTRACT: We present computations of interminiband tunneling rates in semiconductor superlattices. The calculations are based on the time-dependent perturbation treatment under an electric field as developed by Krieger and Iafrate[1]. The electronic wavefunctions are evaluated in the frame of the envelope function approximation, from which is also derived the superlattice miniband structure. Resonances are found for electric fields corresponding to degeneracies in the Wannier-Stark energy spectrum. The influence of disorder is also phenomenologically accounted for in the form of a broadening of the electronic states.

The calculations show that for a few typical GaAs/GaAlAs superlattices one can expect strong interminiband resonances at electric fields well below interband tunneling or avalanche breakdown.

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MP-20 Experimental analysis of diffusion noise in two-dimensional electron layers in HEMTs,* J. Zimmermann, H. Kabbaj, J. Gest, *CHS, Universite de Lille I, Villeneuve d Ascq Cedex, France,* M. de Murcia, and D. Gasquet, *UST Languedoc, Montpellier Cedex, France.* We present an experimental investigation of diffusion noise in 2D electron layers. This point is directly related to the problem of noise figures in heterojunction transistors, but will be seen here more like a fundamental physical phenomenon. A noise measurement setup has been made in order to measure the equivalent noise temperature of the flat resistor represented by the conductive channel of the HEMT, as a function of V_D and V_G (source grounded, gate grounded at radio frequency) . Measurements of S_V and S_I are made at room temperature between 100 MHz and 16 GHz, under DC and/or pulsed drain bias. Measurements are made on standard HEMT's fabricated at the CHS, having L_g=1 μm or L_g=5 μm.

The method generally adopted is without tuning the device: in a first step the reflection coefficient is measured with a network analyzer; in a second step the noise temperature is measured without tuning and then corrected (taking into account insertion losses of the fixture) with the previously measured reflection coefficient.

It is found that the $S_V(V_D,V_G)$ which increases smoothly at low V_D (ohmic regime), saturates at high VD (saturation regime), a saturation effect which follows the drain current saturation. This feature is seen between 8 and 14 GHz. At lower frequencies (F<1.5 GHz), much higher noise powers are measured (in the same conditions), especially in the ohmic regime. But between 100 MHz and 1.45 GHz this noise decreases strongly and thus might be considered as an excess noise due to the source and drain access zones. A first theoretical approach has been realized based on the impedance field method. We found $S_V(V_D,V_G)$ which are in qualitative agreement with experiments, i.e., in the ohmic regime at a given V_D, the S_V increases when V_G decreases, considering a constant diffusion coefficient D_o=150 cm^2/s throughout. A better quantitative agreement 'between theory and experiment would lead to a D which is a function of V_G or of n_S. D would be somewhat lower at low n_S.

* This work is supported in part by contract EEC ESPRIT II BRA 3017.

MP-21 Carrier capture in quantum wells and its importance for ambipolar transport, T. Kuhn and G. Mahler, *Universität Stuttgart, FRG.* The perpendicular transport of optically generated carriers in quantum well heterostructures has been studied recently in several experiments. However, for an interpretation of the data the influence of the capture process on the transport behavior has been neglected. Because of the different length scales of transport profiles and the quantum well width, the well can be modelled as an interface, the description of which depends on the transport model: In a kinetic calculation the microscopic probabilities for transmission, reflection, and capture are used to construct the connection between the distribution functions on each side of the well [1]. In a diffusion equation approach one can define two "interface velocities" which connect the densities and current densities. The well known surface recombination velocity appears as a special case when no transmission is possible. We calculate these interface velocities from the microscopic probabilities in Ref. 1 and demonstrate that agreement between a kinetic and a diffusion approach is very good, provided the excess energy of the laser is small enough to exclude thermal transport effects. By comparison with experimental results we show that a unique determination of the diffusion coefficient and the interface parameters requires measurements at different transport distances.

In AlGaAs the diffusion coefficients and interface parameters of electrons and holes are typically quite different. In analogy to the ambipolar diffusion constant we calculate ambipolar interface velocities from the respective electron and hole velocities. It turns out that in many cases the capture of holes dominates the total capture process. In order to study the validity of the ambipolar approximation we calculate the transport of a two-component electron-hole plasma. In very small samples the transport behavior changes with decreasing power of the laser pulse from an effective one-component (ambipolar) transport to a nearly independent electron and hole transport.

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MP-22 Electron capture in quantum wells: Monte Carlo simulations of transport in infrared photodetectors, M. Artaki and I. C. Kizilyalli, *AT&T Bell Laboratories Allentown, Pennsylvania.* Quantum well photodetectors are of great technological as well as theoretical interest. The absorption properties of these heterojunction devices can be designed by adjusting the dimensions and chemical composition of the constituent materials. In addition to the engineering advantages, this provides a physical system rich in new physical transport phenomena. Recently, GaAs/AlGaAs superlattice photodetectors based on absorption between bound states [1] and between bound and continuum states [2] have been demonstrated.

In this paper we study the transport properties of quantum well photodetectors where the absorbed light excites an electron from the only bound state in the wells to an extended, continuum state. Monte Carlo simulations are used to determine the transport characteristics and calculate the collector current. We have calculated numerically the electron capture rate from a continuum state to a bound state in the envelope function approximation, accounting for the resonances in the incident wave function. The physical mechanisms that we hold responsible for the capture causing collisions are emissions of a polar optical phonon and electron-electron pair collisions. In the calculation of the latter, the final states of both electrons involved in the collision, are assumed to be bound. These rates have been used in a Monte Carlo simulation program which considers transport in the Γ, L and X valleys and also accounts for bulk-like scattering due to acoustic, polar optical and intervalley phonons, as well as ionized impurities. We have assumed that an electron captured into a bound state will remain there and will not be collected at the anode.

We will show results from simulation studies of the device responsivity (proportional to the collector current) as a function of radiation wavelength and device bias. It is shown that the quantum mechanical calculation of the electron capture rate into the wells is necessary to predict the high efficiency of this type of photodetectors. Finally we will discuss the implications on the transport properties if superlattice minibands are formed.

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[2] B.F.Levine, C.G.Bethea, G.Hasnain, J.Walker and R.J.Malik, Electronics Letters, vol.24,747(1988).

MP-23 Indirect excitation processes in two strongly coupled wells, F. Clerot, B. Deveaud, B. Lambert, A. Chomette, A. Regreny, *CNET, LANNION France,* B. Sermage, *CNET, BAGNEUX, France.* The properties of two wells coupled by a thin barrier has become a subject of great interest both due to the possible device applications and to more fundamental aspects. If two wells of the same thickness are coupled by a thin barrier, splitting of the energy levels occurs which directly relates to the intrinsic time constant of the coupling. We report a series of experiments carried out on coupled well systems where the n=l level of the narrow well is close to resonance with the n=2 level of the large well [1,2]. CW luminescence and luminescence excitation (PLE) experiments as well as time resolved studies have been performed as a function of the barrier thickness (varied from 15Å to 100Å). Care has been taken in the sample design as well as in the experimental conditions in order to observe electron transfer.

Here we will not report on the determination of tunnelling time but on the observation of a new series of higher order absorption process in direct gap systems. When the transfer time from the narrow to the large well becomes shorter than the emission time constant of a phonon we can no more directly measure it by time resolved measurements. We then evidence new transitions in the PLE spectra involving indirect absorption of light by an exciton followed by multiphonon cascade in the excitonic system. This kind of transition was theoretically predicted [3,4], and only very partly observed in quantum well systems by Kleinman et al [5]. By varying the barrier width and thus the overall lifetime of an exciton in the narrow well we evidence changes in the relative importance of cascades involving virtual transitions only and cascades involving at least one real transition.

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MP-24 Energy relaxation of light holes in $InAs_{0.15}Sb_{0.85}$/InSb multiple quantum wells,* C. P. Tigges, J. E. Schirber, H. P. Hjalmarson, I. J. Fritz, and L. R. Dawson, *Sandia National Laboratories, Albuquerque, NM.* The energy relaxation rate of light holes in $InAs_{0.15}Sb_{0.85}$/InSb quantum wells has been measured using a Shubnikov de Haas technique. In this type II system, the holes reside in the InSb layers; strain reverses the heavy-light hole ordering and thus light holes are the the charge carriers. The samples consist of 100 InAsSb/InSb periods of thickness 100 Å and 200 Å, respectively; the InAsSb barriers are modulation doped with Be. The total carrier concentration $P \approx 1\times10^{13}$ cm^{-2} is obtained from Hall data. A Shubnikov de Haas technique is used to measure the light hole temperature for a given applied power. The steady state power per carrier is equated to the energy relaxation rate at the measured hole temperature T_H. The measured rate $R \approx T_H^n$ with $n \sim 3.2$. These data are compared with Monte Carlo calculations for this system as well as both theory and experiment for light holes in InGaAs/GaAs quantum wells.

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MP-25 Energy relaxation in GaInAs/InP heterojunctions and GaAs/AlGaAs multiple quantum wells, A. J. Vickers and A. Straw, *University of Essex Colchester, UK.* We have studied energy relaxation in GaInAs/AlInAs heterojunctions and GaAs/AlGaAs multiple quantum wells using both steady state and dynamic techniques. In the steady state the mobility/field and the mobility/temperature curves are used to generate the electron temperature as a function of electric field, from which an energy relaxation time can be derived. In the dynamic experiments we use the pulse on a pulse technique to directly probe the energy relaxation time.

Theoretical calculations of the power loss through acoustic phonons as a function of electron temperature are presented using a two dimensional model. This is fitted to the experimental data using the electromechanical coupling coefficient as the fitting parameter in the warm electron regime. The data is also fitted to an optical phonon power loss theory in the hot electron regime, which gives a value for the optical phonon energy. The fit in both cases is very good.

MP-26 Hot electron energy relaxation via acoustic phonon emission in GaAs/Al$_{0.24}$Ga$_{0.76}$As single and multiple quantum wells, M.E. Daniels, B.K. Ridley, *University of Essex, Colchester, U.K.*, and M. Emeny, *R.S.R.E., Worcs., U.K.* We have investigated the energy relaxation associated with acoustic phonons in a series of modulation doped GaAs/AlGaAs single and multiple quantum wells grown by molecular beam epitaxy, using the hot electron Shubnikov-de Haas effect.

The magnitudes of the magnetoresistance oscillations were measured both as a function of electric field ($0.01<E<5Vcm^{-1}$) at a fixed lattice temperature (2.2K), and as a function of lattice temperature ($2.2K<T_L<20K$) at a fixed low electric field ($E<0.1Vcm^{-1}$). Comparison of these two sets of data allows the electron temperature (T_e) to be plotted as a function of electric field (E), and hence the energy loss rate (P_e) as a function of electron temperature may be deduced. The dependence of energy loss rate on electron temperature was found by plotting P_e versus $T_e^n - T_L^n$.

Two types of material were investigated, the first of high quality exhibiting no parallel conduction and the second showing a marked parallel conduction when in the dark at low temperatures. The persistent photoconductivity effect was used to produce parallel conduction in the high quality samples and to enhance the parallel conduction in the other samples. Shubnikov-de Haas measurements were carried out for both types of material in both the dark and persistent states.

The energy loss rates due to acoustic phonon scattering via both deformation potential coupling and piezoelectric coupling have been calculated. The total energy loss rate as a function of electron temperature is compared with the experimental results. When no parallel conduction is present the energy loss rate is seen to rise above the predicted values at $T_e>12K$. The role of coupled plasmon-phonon modes, which may introduce loss channels competing with those of the acoustic phonons at temperatures below 30K, is discussed. When parallel conduction is present the theoretical curve is seen to give a reasonable fit to the data for $T_e>8K$.

With no parallel conduction the dependence of energy loss rate on electron temperature when $T_e<10K$ and $T_L=2.2K$ was found to be $T_e^2 - T_L^2$, indicating that the phonon distribution at $T_L=2.2K$ is in an intermediate state between the high temperature (equipartition) regime and the very low temperature (Bloch-Gruneisen) regime. When parallel conduction is present, however, the exponents are found to lie within the range $3<n<7$. The effect of parallel conduction and its role in determining the dependence of energy loss rate on the electron temperature is discussed.

MP-27 Experimental and theoretical study of scattering mechanisms for 2D excitons in GaAs/GaAlAs quantum wells, H. Hillmer, A. Forchel, S. Hansmann, M. Morohashi, *Universität Stuttgart, Stuttgart, FRG*, H. P. Meier, *IBM Zürich Research Laboratory, Rüschlikon, Switzerland*, K. Ploeg, *Max-Planck-Institut, Stuttgart, FRG.* We have investigated the scattering mechanisms for 2D excitons in GaAs/Ga$_x$Al$_{1-x}$As quantum wells (QWs) for samples with different well widths ($4nm\leq L_z\leq 90nm$) and varying barrier composition ($0.3\leq x\leq 1$) using a newly developed optical time-of-flight technique [1]. Our studies of the temperature dependence of the exciton mobility in these samples enables us to investigate specific scattering mechanisms of 2D carriers - in particular the interface roughness scattering and barrier alloy scattering. Theoretical calculations based on the quantum well parameters are consistent with the experimentally observed mobilities as a function of temperature for the entire set of samples investigated.

Our optical time-of flight methods permits transport studies in QWs with a very high spatial (~0.1µm) and temporal resolution (~50ps). The high spatial resolution is obtained by microfabricated masks consisting of a light transmittive hole (R>0.5) in an opaque layer. By 8 ps dye laser pulses we create excitons in the QWs within the hole area. The exciton concentration under the hole area is probed time resolved by the radiative emission. Due to exciton transport under the covered parts of the mask the decay of the emission intensity depends strongly on the mask geometry if the hole radius is comparable to the exciton diffusion length. Using the continuity equation including a diffusion and a recombination term we determine the exciton diffusivity and mobility from the time resolved emission profiles. The evaluated mobilities are compared to theoretical calculations for the interface roughness scattering, barrier alloy scattering, acoustic deformation potential and polar optical scattering.

The most important results of our study are:

- For $T<70K$ we observe a strong increase of the mobility $\mu \sim L_z^{2.5}$ for increasing well width. This can be traced to interface roughness scattering arising from microscopic fluctuations of the well widths.
- For temperatures around 100K barrier alloy scattering dominates the transport properties for narrow QWs, where the wavefunctions penetrate deeply into the barriers.
- In the range $x\geq 0.3$ we observe an increase of the mobility with increasing Al-content. Our calculations

demonstrate that this effect is due to the reduced penetration of the wavefunction into the barriers for large x.

- For T>80K the theoretical mobilities calculated for the excitonic deformation potential condition yield the measured well width dependence as well as a good description of the absolute values.

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MP-28 Hot electron electroluminescence in AlGaAs/GaAs heterostructures, C. L. Petersen, M. R. Frei, and S. A. Lyon *Princeton University.* We have observed hot electron electroluminescence in AlGaAs/GaAs heterostructures. Unlike various hot electron transistor structures [1,2], the luminescence experiment gives us sufficient energy resolution to separate out ballistically launched (unrelaxed) electrons from those that have emitted one or more longitudinal optical (LO) phonons. The electroluminescence consists of a series of peaks spaced by one LO phonon energy. In addition to giving us information about the electron distribution, the position of the first (unrelaxed) peak provides a new way to accurately measure the conduction band offset in semiconductor heterostructures.

The structures are grown by Liquid Phase Epitaxy (LPE) on a semi-insulating GaAs substrate and consist of a 3 micron thick p-type (Ge) GaAs layer followed by a 1 micron thick undoped AlGaAs layer and a 1 micron cap layer of n-type (Sn) AlGaAs. The sample-dependent p-type doping density varied from 1.0×10^{17} cm^{-3} to 8.0×10^{17} cm^{-3}, the mole fraction of aluminum varied between 0.28 and 0.32, and the n-type doping in the AlGaAs was about 2.0×10^{17} cm^{-3}. A PIN hetero-diode is formed by etching the AlGaAs from half of the sample, exposing the GaAs layer, and alloying indium contacts into the unetched AlGaAs surface and the etched GaAs surface.

The electrons are electrically injected into the p-GaAs by forward biasing the diode. At low temperatures, the Ge acceptors are largely neutral in the GaAs, providing a well-defined level from which to observe hot electron recombination [3]. When a current is passed through the structure under these conditions, we have been able to observe luminescence peaks which correspond to the initial ballistically launched electron and several successive peaks, each reduced in energy by one LO phonon energy. Since the carriers are electrically injected there are no extraneous luminescence peaks due to Raman and light-hole processes which would be present in a photoluminescence experiment. The observed luminescence differs from the electroluminescence reported in the p-type base region of heterojunction bipolar transistors [4,5].

We can directly observe a ballistic electron without any energy relaxation having occurred. These electrons in the GaAs therefore have an energy corresponding to the minimum of the AlGaAs conduction band. We have used this fact to make preliminary measurements of the GaAs/AlGaAs conduction band offset in a sample with x=0.29. We find an offset of 252meV, in agreement with previous internal photoemission results [6].

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MP-29 Cyclotron phonon emission and electron energy loss rates in GaAs-GaAlAs heterojunctions, D. R. Leadley and R. J. Nicholas, *Clarendon Laboratory, Oxford, U.K.*, J. J. Harris and C. T. Foxon, *Phillips Research Laboratories, Redhill, U.K.* Electron heating and energy loss has been studied in the low temperature region, 0.5K - 10K, in GaAs-GaAlAs heterojunctions. We find the energy loss rate depends on magnetic field which is caused by 'cyclotron phonon' emission. This demonstrates the importance of inter-Landau level transitions as an energy relaxation mechanism.

Previously, electron energy loss has been studied in 2-D systems by a variety of both optical and electrical techniques in the temperature range 10mK - 400K, where in GaAs-GaAlAs heterostructures the loss mechanism is dominated by either optic or acoustic phonon scattering. These studies showed loss rates per electron ranging over 18 orders of magnitude, with several being performed in magnetic field, but no field dependence of the loss rates was observed in the region where acoustic phonon scattering is dominant. The samples used in this study were a series of conventional $GaAs\text{-}Ga_{0.65}Al_{0.35}As$ heterojunctions grown at the Philips Research Laboratories, Redhill, including structures with both single and double subband occupancy. Electron temperatures, T_e, were deduced from the decay in amplitude of the Shubnikov-de Haas oscillations as a function of applied electric field. The high quality samples enabled us to discern Shubnikov-de Haas oscillations at much lower magnetic fields than previous studies, allowing study in the region where the cyclotron energy may be less than kT_e.

In contrast to other measurements using this technique, we find that the electron energy loss rate is strongly dependent on both the magnetic field and electron temperature. When the electron energy is greater than the cyclotron energy the loss rate is enhanced by two orders of magnitude over the high magnetic field case. This is interpreted as a change in the relative importance of intra- and inter-Landau level phonon emission, and the dominance at high T_e of the 'cyclotron phonon' emission process, which becomes very efficient due to the high densities of states at the centres of Landau levels.

At lower electron temperatures or higher magnetic fields we find that the energy loss rate is proportional to $T_e^3 - T_L^3$, and compare this with the behaviour in zero field. From an energy balance picture we deduce an energy relaxation time of $\sim 3\times 10^8$ T $s^{-1}K^{-1}$ and discuss its variation with carrier concentration and upper subband occupation.

TuA-1 Plasma instabilities in quasi-two-dimensional electron gases,* J. B. Stark and P. A. Wolff, *Massachusetts Institute of Technology, Cambridge, MA.* Recent pulsed optical experiments in n-doped quantum wells [1] suggest that hot carriers relax in times as short as 10 fs, whereas p-type or undoped quantum wells require times on the order of 50 fs. While Monte-Carlo calculations [2] can account for the trends in such hot carrier relaxation experiments, times as short as 10 fs are difficult to understand. As an alternative to single-particle relaxation mechanisms, we have considered the possibility of collective mode instabilities in these systems. The dielectric function for a quasi-two-dimensional electron gas is calculated, in the random phase approximation, for a plasma with a nonthermal, excited component. From this function, the plasma eigenfrequencies are determined for the case of a degenerate electron plasma in the presence of electrons excited to energy Eo, above the Fermi energy. Under such excitation, intrasubband plasma modes experience gain by inverse Landau damping, via coupling to the energetic electrons. This behavior contrasts with that of a three dimensional plasma, which is stable to the production of plasmons for any spherically symmetric excited distribution [3]. The instability of two-dimensional plasmons is caused by singularities in the one-dimensional density of states for electrons traveling parallel to the plasma mode. The unstable modes experience amplification at rates on the order of the plasma frequency, relaxing energy from the excited distribution. While these growth rates are not fast enough to account for the observed relaxation rates in n-doped quantum wells, the calculations do indicate an alternative relaxation path, and imply that two-dimensional plasmas are less stable than those in three dimensions. The behavior of the amplified intrasubband modes will be presented as a function of the background and excited plasma distributions, and continuing work described which addresses the response of the intersubband modes.

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TuA-2 Γ-X Intervalley-interlayer scattering rates in type-II GaAs/AlAs superlattices, J. Feldmann, R. Sattmann, E. O. Gobel, *Philipps Universität, Marburg, FRG,* J. Kuhl, J. Hebling, K. Ploog, R. Muralidharan, *Max-Planck-Institut f. Festkörperforschung, Stuttgart , FRG,* P.Dawson, C.T.Foxon, *Philips Research Laboratories, Redhill, U.K.* Short period superlattices (SPS) of $(GaAs)_m(AlAs)_n$ exhibit a transition from a type I superlattice ($m \geq 13$) to a type II superlattice for lower values of m and not too small values of n. In the type II SPS, the lowest confined Γ conduction band states in the GaAs are at higher energy than the lowest confined X conduction band states in the AlAs. After photoexcitation of hot electrons and holes in the confined GAMMA conduction and valence band states of the GaAs, the holes stay in the GaAs slabs during relaxation. In contrast, the electrons scatter from the GAMMA states of the GaAs to the energetically lower X states of the AlAs. The thermalization of electrons thus involves a real space charge transfer from the GaAs across the interface to the AlAs.

We report the direct experimental determination of the transfer times associated with the Γ-X scattering involving a real space charge transfer between different slabs of a superlattice for structures with varying dimensions. For a $(GaAs)_9(AlAs)_9$ SPS and a $(GaAs)_{11}(AlAs)_{24}$ SPS we have performed optical pump and probe experiments with 100 fs time resolution using a white light continuum for the probe. The experimental results of the type II SPS reveal a fast initial partial recovery of the absorption bleaching of the direct exciton of the Γ states in the GaAs, opposite to the results for type I SPS. By simultaneous detection of the bleaching behaviour for different excitonic transitions (heavy hole, light hole, split-off band) we are able to demonstrate that the fast partial recovery results from electron transfer from GaAs into the AlAs. The time constants associated with the electron transfer, however, show a pronounced dependence on the dimensions of the SPS. For instance, we have obtained scattering times of 130 fs and 620-fs for a (9,9) and a (11,24) SPS, respectively. These times are longer than the corresponding $\Gamma \rightarrow X$ scattering time in bulk GaAs, which can be attributed to the spatial separation of Γ- and X-related states. We demonstrate that the $\Gamma \rightarrow X$ scattering times are directly related to the different spatial overlap of the initial and final electronic envelope wavefunctions. As a consequence the $\Gamma \rightarrow X$ scattering rate in type II systems can be tailored by the geometrical dimensions of the sample structure.

TuA-3 Photoluminescence of hot electrons in A_3B_5 semiconductors and QW structures. Determination of scattering times on the femtosecond time scale, D.N.Mirlin, *A.F.Ioffe Physico-Technical Institute, Leningrad, USSR.* The methods of hot photoluminescence (HPL) spectroscopy under cw pumping have been successfully used in recent years to solve a wide range of problems in semiconductor physics. In this paper a survey of the last achievements in the study of the energy spectra and relaxation times will be given.

1. The optical alignment of electron momenta in the process of interband absorption leads to the HPL polarization (ρ). From the magnetic depolarization of HPL the scattering times of intra- and intervalley transitions of hot electrons and the corresponding intervalley coupling constants have been determined for GaAs and InP.

2. Recently similar measurements have been performed for MQW structures $GaAs/Al_xGa_{1-x}As$. For a QW (L_z=70Å, x=0.3) the emission time of LO-phonon by a 2D-electron with the energy $\mathcal{E}$=60meV is 150±10fs. This value is close to the calculated one for the intrasubband scattering. The scattering rate increases with $\mathcal{E}$ due to addition of intersubband 1-2 transitions. The proposed method is not influenced by complicating factors (such as phonon heating and screening). The study of ρ on $\mathcal{E}$ dependence and magnetic field dependence of p in Voigt geometry (B ⊥ z) allows to observe the evolution of the 2D-spectrum in the above-barrier region up to the energy $\mathcal{E}-V_B \approx 2\hbar\omega_{LO}$.

3. The methods of HPL spectroscopy have been used to study the band structure away from the centre of the Brillouin zone. The spin-splitting of the GaAs conduction band versus $\mathcal{E}$ (up to 0.4eV) has been determined. The energy of the side valleys in GaAs and InP, their symmetry and shear deformation potentials have been obtained from the evolution of the HPL spectra under uniaxial deformation. The valence band warping in InP has been determined from the anisotropy of the HPL polarization.

TuP-1 Barrier controlled hot carrier cooling in InGaAs/InP quantum wells, U. Cebulla, G. Bacher, A. Forchel, *4. Phys. Institut, University of Stuttgart,* D. Grutzmacher, *RWTH Aachen, Fed. Rep. Germany,* W.T. Tsang, *AT&T Bell Labs, Murray Hill, U.S.A.* By picosecond time resolved luminescence spectroscopy on $In_{0.53}Ga_{0.47}As/InP$ quantum wells, we have investigated the influence of the quantum well barrier on the thermalization. Previously many investigations have studied the dependence of hot carrier cooling on the quantum well width itself. Our experiments and microscopic calculations demonstrate, that the barrier thickness between the quantum wells has a striking influence on the cooling of the hot carriers. In conjunction with a suitable excitation, this can be used to observe new thermalization phenomena.

In our experiments samples with different well widths L_z (>3nm) and barrier widths L_B (20nm, 400nm) were excited with a pulse compressed Nd-YAG laser at T=2K. For detection in conjunction with the frequency up-conversion technique, an optical multi-channel analyzer was used (time resolution 10ps).

The excitation of the InGaAs quantum wells with a Nd-YAG laser allows the electrons to diffuse into the InP barrier, but keeps the holes confined to the quantum well. For large barrier thicknesses, this leads to a separation of the thermalization time scales of electrons and holes. For small barrier widths on the other hand, no diffusion arises, and a synchronous thermalization of electrons and holes takes place.

From a line shape analysis of the transient spectra, we evaluate the carrier densities and the carrier temperatures Tc as a function of time delay. In the figure experimental data for samples with L_z=7nm and L_B = 20nm and 400nm are displayed and compared to the results of model calculations for the thermalization. Our calculation includes the different scattering mechanisms as well as the barrier influence on the electron capture probability.

Experiment and theory yield striking differences for the carrier temperatures in samples with thin and thick barriers: For small barrier widths (L_B=20nm), the electron density in the quantum wells reaches a maximum within the excitation pulse. This leads to high initial carrier temperatures of $T_c \cong$ 500K. For large barrier widths, drastically lower initial carrier temperatures are observed. In this case, the cooling of the holes occurs first. The delayed capture of the electrons into the InGaAs quantum wells

(L_B=400nm) leads to the formation of a cold electron hole plasma and results in small initial carrier temperatures.

TuP-2 Time-resolved anti-Stokes Raman scattering from inter-subband electronic excitations in GaAs quantum wells, M. Tatham, J.F. Ryan, *Clarendon Laboratory, Oxford, U.K.*, and C.T. Foxon, *Philips Research Laboratory, Redhill.* We have used time-resolved anti-Stokes resonant Raman scattering with picosecond resolution to measure the electron inter-subband transition rate due to emission of longitudinal optical phonons (LO) in GaAs-GaAlAs quantum wells. Electrons were photoexcited by a pump pulse of duration 1 ps, and the sample was probed by a weak time-delayed probe pulse of the same wavelength and duration. The photoexcited carrier density was kept extremely low ($\leq 3\times10^{10}$ cm^{-2}) in order to reduce the effects of electron-electron scattering, which can redistribute electrons among the confined subbands, and also to minimise screening of the electron-phonon interaction which substantially modifies the inter-subband scattering process. In order to detect the weak electronic anti-Stokes spectrum we utilised a resonance in the phonon Raman scattering cross-section which also enhances scattering from the coupled $n = 2 \rightarrow 1$ inter-subband charge density mode. For a sample with well width $L_z = 15$ nm we find the risetime of the electron population in the n = 2 level to be limited by the duration of the pump pulse, which is consistent with very rapid intra-subband relaxation. The n = 2 population then decays with a time constant of $\approx$ 1.7ps. We also observe the transient population of LO phonons emitted by the relaxing carriers to build up during a time of ~ 2ps after the peak of the pump pulse, and then to decay exponentially with a characteristic decay time of 5.5 ps. The dominant $n = 2 \rightarrow 1$ inter-subband relaxation process in GaAs quantum wells for $L_z \leq$ 16nm is predicted to be emission of m = 1 confined LO phonons. The time constant for this unscreened e-LO scattering process is estimated to be 500fs. The difference between this value and the experimental value is likely due to repopulation of the n = 2 level from the n = 3 level by phonon emission, for which the lifetime is estimated to be 1 ps.

TuP-3 Hot phonons in quantum well systems, P. Lugli, *II Università di Roma, Italy,* P. Bordone, S. Gualdi, P. Poli, *Università di Modena, Italy,* S. M. Goodnick, *Oregon State University, Corvallis, Oregon, USA.* We present an investigation of non-equilibrium LO-phonon effects in quantum well systems. Phonon confinements is taken into account by considering explicitly slab modes in the formulation of Fuchs and Kliewer [1]. With respect to the "standard" case, where a tridimensional dispersion is used for the LO phonons, the electron-phonon interaction is reduced as a result of phonon confinement. We use the Monte Carlo scheme already described elsewhere [2], which allows the simultaneous study of the coupled electron and phonon dynamics, without requiring any sort of assumptions on the respective distribution functions. It should be pointed out that the quantization of the phonon wave vector in the direction perpendicular to the interfaces completely solves the normalization problem for the hot-phonon calculation in 2D-systems. For the case of photoexcitation in AlGaAs-GaAs quantum wells we observe a reduction in the cooling rate due to the reabsorption of hot phonons. The dependency of the cooling process on the well width and on the excitation conditions will be discussed in the paper. The case in which a high electric field is present (which requires a two-dimensional grid for the hot phonon counting) will also be dealt with.

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TuP-4 Dynamics of the inter-subband relaxation of thermalized carriers in GaAs/AlGaAs multiple quantum wells, J. A. Levenson, G. Dolique, J. L. Oudar and I. Abram, *Centre National d' Etudes des Telecommunications, Bagneux, France.* We have measured the inter-subband relaxation times in GaAs/GaAlAs Multiple Quantum Wells, through pump-and-probe experiments [1] which use picosecond light pulses to inject a dense electron-hole gas in specific subbands and then follow the time evolution of the bleaching due to this gas. We find that the inter-subband relaxation is slowed considerably for transitions between states separated by less than the energy of 1 LO phonon. However, we measure characteristic relaxation times of the order of 20 ps even in the case in which the inter-subband splitting is smaller than the LO phonon energy. This result contrasts with other published experiments [2] which (under identical conditions) find an inter-subband relaxation time for electrons, of the order of 500 ps. As our experiments measure a joint electron-hole relaxation time, this difference reflects the faster relaxation of the holes and points to specific energy-loss mechanisms to which holes can participate.

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TuP-5 Intersubband relaxation of hot carriers in semiconductor quantum wells, J. Lary and S. M. Goodnick, *Oregon State University, Corvallis, OR,* and Paolo Lugli, *II Università di Roma, Italy.* Using an ensemble Monte Carlo simulation of coupled electrons, holes and nonequilibrium slab mode polar optical phonons in single and multiple quantum well systems, we have studied the relaxation of hot carriers in ultra-fast optical intersubband relaxation experiments [1-3]. In all cases, the dominant intersubband transfer mechanism is due to polar optical phonon scattering (for electrons), with intercarrier scattering playing a relatively minor role. Our simulated results using self-consistent envelope functions in the quantum well system show the importance of nonequilibrium hot phonons and self-consistency in explaining the experimental results from time resolved Raman [1] intersubband absorption [2], and photoluminescence spectroscopy [3]. For wide wells with subband separation less than the optical phonon energy [1], we find that long time constant occupation of upper levels results from the thermal tail of the heated carrier distribution due to hot phonon effects and not an intersubband bottleneck. For narrow, modulation doped, samples [2], long time constant decay from the second subband arises from localization of the envelope function in the barrier material due to the attractive potential of ionized donors in that region. Finally, we have studied intersubband relaxation in asymmetric coupled quantum wells, where we find very long time constants.

TuP-6 Quasi-analytical simulation of ultrafast relaxation of photoexcited electrons in a semiconductor quantum well, T. F. Zheng, W. Cai and P. Hu, *City College of the City University of New York, New York,* and M. Lax, *City University of New York, New York, and AT&T Bell Laboratories, Murray Hill.* We propose an analytic function approach to study the system of electron and phonon relaxation during an ultrafast process in GaAs-$Ga_xAl_{1-x}As$ heterojunction. Gauss-type energy functions are used to simulate the peaks of nonthermal electrons, while the background electrons are described by a Boltzmann distribution function. The time variation of parameters describing the amplitudes, widths of Gauss-type functions and the temperature of background electrons are determined by solving the Boltzmann equation with electron-electron and electron-phonon interactions. Our choice of analytic distribution function made the calculation simple: only one integral over a two-dimensional momentum **q** need be numerically handled. After carrier-carrier thermalization, our results automatically reduce to that of the electron temperature model. As a first application we have calculated the relaxation of low energy photo-excited pumping by use of an approach including only four parameters. In contrast to the approach by Esipov and Levinson in ref. 1 our method does not require that the excited electrons be a small fraction of the background electrons. Since the electron-electron collisions among excited electrons are properly considered, our approach can be used for an arbitrary proportion of excited electrons and background electrons.Our results show in reasonable agreement with that of the Monte-Carlo calculation in ref. 2.

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TuP-7 Monte Carlo simulation of femtosecond spectroscopy in semiconductor heterostructures, S. M. Goodnick, *Oregon State University, Corvallis, OR,* P. Lugli, *II Università di Roma, Italy,* W. H. Knox and D. S. Chemla *AT&T Bell Laboratories, Holmdel.* We have used an ensemble Monte Carlo simulation of quantum well systems to interpret the complicated carrier dynamics of low energy excitation time resolved absorption experiments in semiconductor quantum wells. We include the multi-subband electron-electron, electron-hole, and hole-hole scattering rates in order to realistically model the photoexcited electron-hole dynamics and absorption spectrum during and after the pump pulse. Intercarrier scattering due to electron-electron interaction is found to dominate the relaxation in accordance with the H-theorem for the time evolution of an isolated nonequilibrium system. The H-function itself is found to be dominated by the generation of electrons and holes with a relatively small contribution due to the entropic change associated with relaxation. The results of this simulation compared to experimental data on undoped, n and p modulation doped narrow wells is in good qualitative agreement, particularly at lower injection densities. Quantitative agreement is found to be sensitive to experimental parameters related to pulse duration, excitation density, and exciton bleaching which are difficult to measure precisely. Comparison to high density excitation experiments (n_{inj}>$5\times10^{11}/cm^2$) is further complicated.

TuP-8 Intersubband dynamics in modulation doped quantum wells, J. L. Educato, A. Sugg, D. W. Bailey, K. Hess and J. P. Leburton, *University of Illinois at Urbana-Champaign.* Recently, intersubband relaxation in modulation doped GaAs/$Al_zGa_{1-z}As$ multiple quantum well structures (MDMQWS) has been observed directly by an infrared bleaching technique [1]. The intersubband time constants determined experimentally are surprisingly long (≈ 10 ps). But, as well width increases, electron lifetimes decrease. A well width change from 47 Å to 59 Å results in approximately a factor of two decrease in relaxation time. A theoretical investigation of the dynamics of intersubband transitions in n-type $GaAs/Al_zGa_{1-z}As$ MDMQWS by emission of polar optical phonons is presented. Electronic properties and wavefunctions are obtained from the barrier matrix technique extended to MDMQWS. The electron-phonon interaction in the well and the barrier are treated within the Fröhlich Hamiltonian formalism for dielectric slabs. The carrier dynamics are simulated by Monte Carlo. In n-type MDMQWS, the space charge resulting from positively ionized donors induces conduction band minima in the barriers which contain several bound states. In narrow wells, the upper subband interacts with the eigenstates of the barrier and causes a delocalization of the upper subband wavefunction into the AlGaAs barrier. This interaction leads to increasing probability for excited carriers to reside in the barriers and relax to the ground state with emission of AlGaAs LO phonons. Thus, emission and absorption transition rates between all subband and within themselves are calculated in both wells and barriers. Monte Carlo simulations have shown that for narrow wells the dominant transition rate to the ground state involves a wavefunction that is not bound to the well and the AlGaAs phonon transition dominates. For wider wells, the dominant transition rate involves a wavefunction that is more equally shared between the barrier and the well. Monte Carlo has also shown the importance of the initial electron distribution on the relaxation mechanism and, ultimately, the time constants. The interplay between carriers in different subband is critical in determining the time evolution of subband populations.

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TuP-9 Intersubband absorption of hot electrons in a modulation-doped $Ga_{0.47}In_{0.53}As/Al_{0.48}In_{0.52}As$ multiple-quantum-well structure, T. Elsaesser and R. J. Bauerle, *Technischen Universität München, Federal Republic of Germany,* H. Lobentanzer, W. Stolz, and K. Ploog, *Max-Planck-Institut fur Festkörperforschung, Stuttgart, Federal Republic of Germany.* Transient intersubband absorption spectra of hot electrons in a n-doped $Ga_{0.47}In_{0.53}As/Al_{0.48}In_{0.52}As$ multiple-quantum-well structure (electron density 4×10^{11} cm^{-2} per QW) are studied by picosecond infrared spectroscopy. Additional electron-hole pairs with an excess energy of 0.3 eV are generated by picosecond interband excitation in the near infrared (excitation density $N\leq4\times10^{11}$ cm^{-2}). The excited electrons relax within less than 3 ps to the lowest conduction subband [1] resulting in a hot electron gas in the n=1 band. The absorption line of the transition between the n=1 and n=2 conduction subbands, which is located around 0.15 eV, is studied by delayed probe pulses of variable frequency to detect changes of the band shape with the transient temperature of the carriers. We find an increase of the spectral width from 60 cm^{-1} to approximately 120 cm^{-1} for a rise of carrier temperature from 10 K to 400 K. This strong broadening relaxes - parallel to carrier cooling - on a time scale of several tens of picoseconds. The change of the absorption band is related directly to the different nonparabolicity of the two conduction subbands. The distribution of hot electrons extends over a broad interval in k-space. At large k-values, the energy of the intersubband transition is different from that around k=0 leading to a distinct new bandwidth of the transition. The data are analyzed by model calculations and compared to steady state measurements of the intersubband absorption [2].

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TuP-10 Hot carrier thermalization in GaAs/AlAs superlattices, K. Leo, W. W. Rühle, and K. Ploog, *Max-Planck-Institut fur Festkörperforschung, Stuttgart, Federal Republic of Germany.* The carrier-lattice thermalization of laser-generated electron-hole plasmas is studied in *semiconductor superlattices* by time-resolved luminescence in the ps regime. It has been suggested [1,2] that the polar-optical (Fröhlich) interaction of carriers and LO-phonons is significantly reduced in such artificially layered structures. Three different GaAs/AlAs multilayer samples grown by MBE are compared: The GaAs layer thickness is kept constant (6nm), the AlAs thickness is varied (5.6, 2.0, and 1.1 nm). This approach allows to study differences between Quantum Wells (QW's) with quasi-two-dimensional and superlattices with three-dimensional carrier systems. The phonon emission and absorption rate is determined by tracing the plasma temperature gained from the luminescence spectra. Two types of experiments are performed: Firstly, a hot plasma is created in a cold lattice and the cooling process is traced and, secondly, a cool plasma is created by resonant excitation in a warm lattice and the heating is traced. An analysis of the thermalization curves with an algorithm including all phonon scattering processes reveals the LO-phonon emission and absorption rates. The net energy-transfer rate by LO-phonons (ETR_{po}) in the cooling experiment depends strongly on the excitation density: In all structures, it is reduced at high densities ($\sim 10^{12}cm^{-2}$) up to a factor of 100, probably by reabsorption of "hot" phonons, as already observed in bulk material and QW's. At low densities, the phonon emission comes close to the theoretically predicted rate (without screening, phonons in equilibrium). Only the superlattice sample (1.1nm AlAs thickness) shows a slightly reduced cooling rate, probably due to carrier diffusion in regions with lower energy. In the heating experiment, the phonon *absorption* rate is identical for all samples. At higher densities, it is reduced. This reduction can be ascribed to an *under*-population of the phonon modes involved in the scattering ("cold" phonons). The results are compared with a detailed theoretical calculation of the coupled carrier-phonon system including a nonequilibrium between electron and hole temperatures. The theory fits reasonable for electrons. In case of holes, additional effects must play a role. In conclusion, these results show that the LO-phonon-carrier interaction is (within our experimental accuracy of about 30%) *equal* in a superlattice, QW's and bulk material and that nonequilibrium effects of the phonon system are important in plasma cooling *and* heating experiments.

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TuP-11 Screening of the n=2 excitonic resonance by hot carriers in an undoped $Ga_{0.47}In_{0.53}As/Al_{0.48}In_{0.52}As$ multiple quantum well structure, H. Lobentanzer, W. Stolz, K. Ploog, *Max-Planck-Institut fur Festkörperforschung, Stuttgart, Federal Republic of Germany,* T. Elsaesser and R.J. Bauerle, *Technischen Universität München, München , Federal Republic of Germany.* Screening of the n=2 excitonic resonance by hot carriers is investigated simultaneously with intersubband scattering and carrier cooling in an undoped $Ga_{0.47}In_{0.53}As/Al_{0.48}In_{0.52}As$ multiple quantum well by means of picosecond infrared spectroscopy. In different experiments free carriers are generated in the first and second subband as well as in the first subband alone by an intense pumping pulse, whereas the changes in the absorption spectrum is monitored by a weak probe pulse as a function of wavelength and temporal delay. The electrons in the n=2 subband are scattered rapidly (≤3ps) into the n=1 subband as reported recently also for a n-type modulation doped sample[1]. The subsequent cooling of the hot electron -hole plasma occurs with a time constant of several tens of picoseconds in agreement with results obtained by time-resolved photoluminescence [2]. A strong screening of the n=2 excitonic resonance is observed, which disappears with a decay time of around 30ps. Since this time is comparable to the cooling time of the hot electron-hole plasma, we conclude, that the observed screening of the n=2 excitonic resonance is neither caused by the electrons in the n=2 subband (lifetime ≤3ps) nor by the existence of a cold electron-hole plasma (lifetime ≅ 2ns), but is identified as a hot carrier effect.

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TuB-1 Are transverse phonons important for intervalley scattering?, S. Zollner, J. Kircher, M. Cardona, *Max-Planck-Institut für Festkörperforschung, Stuttgart, FRG,* S. Gopalan, *The University of Western Ontario, London, Ontario, Canada.* We have performed a theoretical analysis of intervalley scattering in GaAs and GaP, including realistic models for the phonons and a pseudopotential band structure. It is our purpose to study the effects of details of the band structure and identify the nature of the intervalley phonons. Recently we have calculated the intervalley deformation potentials for the transitions between the Γ-point (not valley) and *X*- or *L*-points. We extend these calculations to study how the DP's change when one moves away from **k**=0. For *L*-Γ-scattering in GaAs we find that the sum of all longitudinal (LA and LO) processes is independent of **k** ($D_{L\Gamma}$ = 6 eV/Å), whereas the sum of the two TA modes increases with |**k**| and reaches about 2 eV/Å. In order to describe an intervalley scattering experiment it is necessary to take into account the k-dependence of the phonon energies, the deformation potentials, and the band structure and to perform an integration over the whole Brillouin zone. We have used the tetrahedron method to do this and find three distinct peaks in the intervalley phonon density of states (TA, LA, and LO phonons), with the TO contribution being negligible. The relative importance of the different phonon modes for Γ-*X*-scattering can be found by studying the temperature dependence of the broadenings of the E_0 critical point in an indirect material (here GaP), obtained from an analysis of the dielectric function measured with ellipsometry. Experimental data indicate that the TA phonon contribution is small, but not insignificant.

TuB-2 Hot electron magnetophonon spectroscopy of semiconductors in high magnetic fields up to 40 T, Koji Yamada[a,b], Noboru Miura[a], Chihiro Hamaguchi[c] and Norihiko Kamata[b], *(a) University of Tokyo, Japan, (b) Saitama University, Japan (c) Osaka University, Japan.* We have developed a new technique for measuring the hot electron magnetophonon resonance (MPR) in pulsed high magnetic fields up to 40 T. Employing a transient recorder with 16 bit resolution combined with a computer-aided data processing system, magnetophonon oscillation can be measured much more accurately than previous measurements including many fine structures. Many new features of the hot electron process were found in various systems. In n-Si, the MPR oscillation, originating from the many-valley transitions were observed in the longitudinal configuration at 80 K for B||<100>, <110> and <111> axes. Owing to the high resolution and high magnetic fields, each resonance peak can be assigned to a specific electronic transition. The oscillation consists of many series corresponding to different transitions. For B||<100>, the oscillation was mainly governed by the f-II0Σ_3 phonon (47.4 meV) process with a fundamental field B_F=82 T, whereas for <110>, the series with B_F=106 T shows the dominant series with the same f-II0Σ_3 phonon. The electric field dependence of the magnitude of each series showed an interesting behavior reflecting the scattering mechanism.

In p-InSb, many new transition peaks were observed for B||<100> and <111>, and they are found to be in excellent agreement with theoretical calculation based on the Pidgeon-Brown model. In short channel $n^+n^-n^+$ InP samples, the reversal of the MPR resonance peaks from maxima to minima was observed in high electric fields, due to the splitting of each MPR peak. The electric field dependence of the splitting was measured in high electric and magnetic fields and explained based on the quantum transport theory.

TuP-12 Polar-optical-phonon scattering of charge carriers in alloy semiconductors: Effects of phonon localization,* L. F. Register(a), M. A. Littlejohn(a,b), and M. A. Stroscio(b,a), *(a)Electrical and Computer Engineering Department, North Carolina State University, Raleigh North Carolina 27695-7911, (b) U.S. Army Research Office, Research Triangle Park North Carolina 27709.* The effects of phonon localization on polar-optical-phonon scattering of charge carriers in zinc blend semiconductor alloys of the type $A_xB_{1-x}C$ are modeled analytically. First, as a foundation for what follows, it is demonstrated that alloy disorder implies a spread in the crystal momentum of individual phonon modes that in turn implies an uncertainty in the change in crystal momentum of charge carriers scattered by absorption or emission of these phonons. However, to within the accuracy of the model used, it then is demonstrated that the total polar-optical-phonon-induced carrier transition rate between given carrier crystal momentum states should exhibit little effect of phonon localization, despite the uncertainty in the carrier momentum change for individual scattering events. Here, no specific form for the phonon localization is assumed. Rather, calculations rely on the inherent spatial orthogonality and mathematical completeness of the vibrational modes and the approximately constant energy of the phonons within either AC-like or BC-like optical branches of the phonon spectrum, whatever the specific nature of the localization may be. Finally, the significance of these results to the modeling of hot carrier transport in bulk alloys and heterostructure devices is discussed. This work has been supported by the Office of Naval Research, the Semiconductor Research Corporation and the National Science Foundation through the Engineering Research Center Program.

TuP-13 Hot-phonon-hot electron coupled Boltzmann equations in GaAs and in InP, M. Fadel[a)], M. Rieger[b)], J. C. Vaissiére[a)], J. P. Nougier[a)], P. Kocevar[b)]; *a) Centre d'Electronique de Montpellier[c)], USTL, Montpellier, France, b) Institut für Theoretische Physik, Universität Graz, Austria.* In GaAs, at electric fields between 2 and 5 kV/cm, polar optical phonons (PO phonons) are heated by hot electrons. In turn, this phonon distribution disturbance modifies the hot electron distribution, so as electron transport coefficients. Very recently, Monte Carlo algorithms have been developed in order to evaluate these deviations [1,2].

The purpose of this paper is to study these effects using a direct numerical technique for solving the non linear coupled hot-electron hot-phonon Boltzmann equations (BE), which write, in the steady state:

$$\hat{C}_{ph}N(\mathbf{q}) - \hat{D}_{ph}N(\mathbf{q}) - \frac{N(\mathbf{q})-N_L}{\tau_L} = 0 \quad (1)$$

$$-\frac{eE}{\hbar}\nabla_k f_1(\mathbf{k}) + \hat{C}_{11}f_1(\mathbf{k}) + \hat{C}_{12}f_2(\mathbf{k}) - \frac{f_1(\mathbf{k})}{\tau_1(\mathbf{k})} = 0 \quad (2)$$

$$-\frac{eE}{\hbar}\nabla_k f_2(\mathbf{k}) + \hat{C}_{22}f_2(\mathbf{k}) + \hat{C}_{21}f_1(\mathbf{k}) - \frac{f_2(\mathbf{k})}{\tau_2(\mathbf{k})} = 0 \quad (3)$$

where eq.(1) is the BE for the phonons, eqs.(2) and (3) are the BE for the electrons in the Γ and in the L valley. This system was solved using an iterative procedure and a combined matrix and least square method, generalizing [3] to a two valley model. The main advantage of this method is its great accuracy, compared with other methods used till now. Results have been obtained in InP and in GaAs at 300 K.

The phonon distribution N(**q**) shows important deviations from the thermal equilibrium one, the shape of N(**q**) depends on the orientation of **q** with respect to the field E. The electron distribution f(**k**) is significantly modified by hot phonons, with respect to its value obtained neglecting, as usually, hot phonon effects. As a consequence, one might expect a non-negligible effect on transport coefficients.

c) Laboratoire associé au Centre National de la Recherche Scientifique (UA 391). This work was partially supported by a French European Network.

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TuP-14 A many-band silicon model for hot-electron transport at high energies, R. Brunetti, C. Jacoboni, *Dipartimento di Fisica, Università di Modena,Via Campi 213/A, 41100 Modena, Italy,* F. Venturi, E. Sangiorgi, and B. Riccò, *DEIS, Università di Bologna,Viale Risorgimento 2, Bologna, Italy.* When in electron transport very high energies ($\varepsilon \geq 1$eV) are reached, the traditional models used in Monte Carlo simulations for band structure and scattering mechanisms are no longer adequate. Some attempts at improving the traditional calculations based on a single (non-) parabolic band have been proposed [1,2], but they lead to large amount of computations unsuitable for the simulation of real devices in dynamic technology development.

This paper presents a new Monte Carlo scheme for high electric field electron transport in Si particularly devised to achieve a good trade-off between accuracy and computation time. The model features an original electron band structure consisting of three isotropic parabolic upper bands (two of them are "hole like"), together with the lowest nonparabolic band in a finite spherical Brillouin zone. The bands are given by analytic expressions whose parameters are fixed by best fitting the density of states taken from band structure calculations [2] as a function of energy up to 3eV.

Such a model is consistently used in electron dynamics and in the evaluation of the scattering probabilities. In particular electrons can move from one band to another not only by scattering but also because of the action of the electric field. The coupling constants to the scattering agents are determined by best fitting the available experimental data on transport properties.

Results for electron transport in bulk silicon will be shown, and the effect of the new features of the model will be discussed.

The Monte Carlo scheme described in this paper is being implemented in a two dimensional simulator for MOS devices [3].

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TuP-15 Effect of the degeneracy on the transport of hot holes in silicon, A. Moatadid, J.C. Vaissiére, J. P. Nougier, *Centre d'Electronique de Montpellier*, Université des Sciences et Techniques du Languedoc, 34060 Montpellier Cedex, France.* In scaled-down structures (inversion layers, heterojunction devices, etc...) the free carrier density is very large. The purpose of this paper is to take into account the degeneracy alone, all other phenomena (carrier-carrier interactions, etc...) related to high carrier density being neglected.

For this purpose, the degenerate Boltzmann equation is for the first time solved numerically, in the presence of an electric field. To solve this strongly nonlinear equation when $f(\mathbf{k},t)$ is not negligible compared to 1, we generalized the method settled in the laboratory.

The semiconductor studied here is p-type Silicon. We used a single spherical parabolic band model, with an electric field dependant effective mass to account for the real energy bandshapes, with elastic acoustical phonon, non polar optical phonon, and impurity scattering mechanisms. The Boltzmann equation was solved "without degeneracy", i.e. dropping the factors $[1-f(\mathbf{k},t)]$ and $[1-f(\mathbf{k}',t)]$, and "with degeneracy", i.e. taking into account the complete equation. The results are the following:

- The effect of the degeneracy, on the hot carrier distribution function, becomes noticeable above a free carrier concentration of $p_0=5\times10^{18}$ cm^{-3}. It is quite important at $p_0=10^{20}$ cm^{-3}.
- The drift velocity is not significantly affected by degeneracy. Conversely, the average energy strongly depends on degeneracy.

This suggests that the degeneracy should be much more efficient in many-valley semiconductors, and in confined layers (inversion layers, heterostructures,...), than in Silicon. This will be studied in the future.

*Laboratoire associé au CNRS, UA391. This work was partially supported by the Groupement Circuits Intégrés Silicium (GCIS).

TuP-16 Weighted ensemble Monte Carlo, L. Rota, C. Jacoboni, P. Poli, *Dipartimento di Fisica, Università di Modena, Via Campi 213/A, 41100 Modena, Italy.* We present a new powerful method, called Weighted Ensemble Monte Carlo (WEMC), for the solution of electron transport problems in semiconductors. The method is formally derived from an iterative expansion of the integral form of the Boltzmann Equation. With this algorithm we are still dealing with flight durations and scattering mechanisms, like in standard Monte Carlo methods, but we can choose arbitrarily the probabilities of these events. Thus, we can select the initial state where it is most convenient and "guide" the electrons to regions of k and r space we are interested in.

This method is much more flexible than the standard Monte Carlo algorithm (that can be considered as a special case of WEMC) and can be used to focus the computation to any particular aspects of interest. In particular it can be useful to study the distribution function in regions of (**k**, **r**) space where electrons go very rarely.

In the present work we have applied the method to study the high energy tail of the distribution function, bringing electrons to energies so high that are not reachable with normal Monte Carlo programs. Also space dependent problems have been investigated forcing electrons to climb over a high potential barrier; in this way we can study with great detail the energy distribution and other parameters in front of and behind the barrier.

TuP-17 Direct Monte Carlo simulation of hot-carrier conductivity, Lino Reggiani and Luca Varani, *Dipartimento di Fisica e Centro Interuniversitario di Struttura della Materia, dell'Università di Modena, Via Campi 213/A, 41100 Modena, Italy,* Vladimir Mitin, *Institute of Semiconductors, Academy of Sciences of the Ukrainian SSR, Kiev, USSR.* One of the main limitation in using Monte Carlo simulations is to treat the case of a field independent carrier concentration. Thus, once the drift velocity versus field is obtained, the calculation of conductivity (one of the most accessible experimental data) is straightforward inferred from the knowledge of the sample geometry and the equilibrium carrier concentration. However, at lowering temperature and/or increasing doping concentration partial freeze-out of the ionized impurities occurs and the well-known phenomenon of field-assisted ionization is observed under hot-carrier regime. As a consequence, the calculation of the conductivity requires the knowledge of the free carrier concentration at the given field. Within a single impurity approach (Hydrogenic-model) two effects concur in determining the carrier concentration. Firstly, the field dependence of the recombination rate induced by carrier heating. Then, the modification of the impurity potential (the so called Poole-Frenkel effect) which implies a field dependent generation rate.

In this communication we present a Monte Carlo procedure which, by including the mechanism of generation and recombination from impurity centers, enables us to calculate directly from the simulation the field dependent conductivity for the first time. In particular, the field dependent carrier concentration, lifetime and mobility are naturally provided by the calculation. (We remark that our procedure consistently accounts for the effect of generation-recombination processes on the free carrier mobility.) The reliability of the theoretical model has been checked by comparing numerical results with experiments provided by the Montpellier group and performed on p-Si at different acceptor concentrations and temperatures. The excellent agreement found fully supports the theoretical model which confirms the importance of the cascade capture mechanism assisted by acoustic phonons in determining the carrier concentration.

TuP-18 Energy exchange via electron-electron scattering in many-valley semiconductors, L. Rota, *Dipartimento di Fisica, Università di Modena, Via Campi 213/A, 41100 Modena, Italy,* P. Lugli, *Dipartimento di Ingegneria Meccanica, II Università di Roma, Via O. Raimondo, 00173 Roma, Italy.* The theoretical treatment of electron-electron (e-e) scattering in semiconductor transport has always posed formidable problems, due to the long range and to the non-linearity of the interaction. For a long time, it has been thought that the conservation of total energy and momentum would not lead to significant effects on the transport properties. Recent time-resolved optical measurements have evidenced the importance of the interparticle interaction in the relaxation of photoexcited electrons. There, the interaction leads to an internal thermalization of the distribution much more rapid than the dissipation process to the lattice. We present here a Monte Carlo study of the e-e interaction based on a molecular-dynamics approach. The full long range of the Coulomb interaction is accounted for, and no assumptions are needed on the screening process. This is particularly important when different valleys are involved, and a multi-component plasma has to be simulated.

The Monte Carlo algorithm has been applied to the study of the relaxation of photo-excited electrons in GaAs. When the excitation energy is sufficiently high, an appreciable transfer of photoexcited electrons occurs from the G into the L-valley. The interaction between the two populations (light hot electrons in G and heavy cold electrons in L) is very strong at densities above $10^{17}cm^{-3}$. During the cooling process, energy is transferred via electron-electron scattering from the central to the satellite valley. This energy transfer leads to a very rapid cooling of the Γ-valley population. It should be emphasized that such type of interaction has never been considered up to now in Monte Carlo simulations.

The dependence of the electron-electron interaction on the excitation condition will be discussed in detail. A comparison with a different approach, where the e-e scattering is treated in k space using a screened potential formulation, will also be presented.

TuP-19 Electron-beam induced conductivity at high electric fields in GaAs, C. Panhuber, H. Heinrich, H. Thim, K. Lübke, *Johannes Kepler Universität, A-4040 Linz, Austria.* Electron-Beam-

Induced-Current (EBIC) measurements with application of a bias proved to be a valuable tool in investigating band-edge discontinuities in heterostructures [1]. With high bias in the vicinity of the flat-band voltage, part of the bias drops in the bulk section of a heterodiode. In this case, electron-hole pairs generated by the electron beam produce a current in the bulk which is in opposite direction to the EBIC and might obscure the evaluation of the flatband voltage [2]. We report about the investigation of this Electron-Beam-Induced Conductivity (EBICO) in MOCVD-grown GaAs samples of 3-8 μm length at electric fields up to 1300 V/cm. We find that this EBICO-signal is less than 1/20 of the EBIC signal at typical hetero-junctions. In addition, EBICO - which is in principle similar to photoconductivity - turns out to be a valuable tool in investigating minority carrier diffusion at high electric fields. Due to the very local excitation of e-h pairs by the electron beam (approx. 1 μm width) it is possible to scan the EBICO-signal from the vicinity of the contacts into the bulk of the sample. In this case, recombination (at the contacts and in the bulk) as well as drift governs the structure of EBICO. By comparison of the observed scans with model calculations, it is possible to determine the diffusion length and lifetime of minority carriers (holes) as a function of applied electric fields. In the range of 50-1300 V/cm, we find a decrease of the lifetime of about 0.5 to 0.2 ns for our samples of GaAs.

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TuP-20 Photoemmision of metal-semiconductor structures: novel spectroscopy for high field transport, J. Peretti, D. Paget and H.-J. Drouhin, *Laboratoire de Physique de la Matiere Condensee, Ecole Polytechnique, 91128 Palaiseau Cedex, France.* We measure the energy distribution curve (EDC) of electrons photoemitted into ultra-high vacuum from a metal-semiconductor structure for which the vacuum level has been lowered by cesium and oxygen coadsorption. Photoelectrons created in the bulk of the semiconductor by nearbandgap light excitation are injected into the band bending region (BBR) with a negligible kinetic energy and can be emitted into vacuum after crossing the thin metallic layer (100Å of silver), which essentially does not modify their energy. The figure gives experimental results for the case of p-type InP ($N_A=10^{16}$ cm^{-3}) at 120K with a maximum bias of 2.7 V applied to the structure. Together with the EDC obtained for this bias, EDC's obtained for a smaller bias are represented inside the solid at a distance from the bulk corresponding to the known width of the BBR for this bias. Thus, the measure of the EDC in vacuum as a function of bias allows to follow the progression of the EDC in the solid across the BBR. In addition to the principal maximum, these EDC's exhibit high-energy structures which can be followed as a function of distance, allowing a spectroscopic analysis of high-field electron transport. From an analysis of the experimental data we derive the relevant parameters for electron transport.

TuP-21 Transverse Diffusion coefficient and carrier density fluctuation derived from the fluctuation of the state occupancy function in semiconductors, J. P. Nougier, J. C. Vaissiére, *Centre d'Electronique de Montpellier(*), Universite des Sciences et Techniques du Languedoc, 34060 Montpellier Cedex, France.* The state occupancy function [1] is the random function $f(\mathbf{k},\mathbf{r},t)$, defined in a domain $\mathcal{D}$ around $\mathbf{r}$, which takes the value 1 if the state k is occupied by an electron, and 0 if it is empty. $f(\mathbf{k},\mathbf{r},t)$ fluctuates about its average value $f_S(\mathbf{k},\mathbf{r})$, which is the solution of the steady state Boltzmann equation (BE). The classical theory [2], which had been accepted till now by everybody, assumes that $f(\mathbf{k},\mathbf{r},t)$ is Markovian: this implies that the number of carriers $N(\mathbf{r},t)$, which are at time t in the domain $\mathcal{D}$, does not fluctuate, which is obviously wrong. A consequence of this classical assumption is that the Langevin noise source [2] term $S_\xi(\mathbf{k},\mathbf{k}')$, is given (see eqs. (12.24) and (12.25) of ref. [2]) by the nondiagonal expression:

$$S_\xi(\mathbf{k}_1,\mathbf{k}_2) = \delta_{\mathbf{k}_1\mathbf{k}_2} \times \left[\sum_{\mathbf{k}} f_S(\mathbf{k})P(\mathbf{k},\mathbf{k}_1)+\sum_{\mathbf{k}} f_S(\mathbf{k}_1)P(\mathbf{k}_1,\mathbf{k}) \right] - \left[f_S(\mathbf{k}_1)P(\mathbf{k}_1,\mathbf{k}_2) + f_S(\mathbf{k}_2)P(\mathbf{k}_2,\mathbf{k}_1) \right] \quad (1)$$

Using the fact that $N(\mathbf{r},t)$ fluctuates, we recently demonstrated that eq. (1) cannot hold. Instead, we proposed [1 for $S_\xi(\mathbf{k},\mathbf{k}')$ the expression:

$$S_\xi(\mathbf{k}_1,\mathbf{k}_2) = S_\xi(\mathbf{k}_1)\,\delta_{\mathbf{k}_1\mathbf{k}_2} \quad (2)$$

The purpose of this paper is to compare the expressions of the fluctuation of the number of carriers, and of the transverse diffusion coefficient, derived using either eqs. (1) or (2), which has never been done yet. The transverse diffusion coefficients $D_\perp(E)$ are computed in pure p-type Si at 300 K, using eqs. (1) and (2) together with the differential relaxation time formalism, and are compared with a Monte Carlo simulation, up to 50 kV/cm. The discrepancy between the present and the classical theories is small: although the accuracy of the present theory, with respect to Monte Carlo simulation (MC), seems to be better, one cannot assert, in the present state of the art, that the discrepancy between MC and the classical theory lies beyond computational uncertainty. both theories give, in the perturbation approach, ohmic values $D_0=13.7\ cm^2/s$ in agreement with the Einstein relation and with MC simulation.

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(*) Laboratoire associé au CNRS (UA 391). Work was partially supported by the GCIS.

TuP-22 Autosolitons in electron-hole plasma weakly heated by electric field, M. N. Vinoslavskii, B.S.Kerner, V.V.Osipov, O.G.Sarbei, *Institute for Physics, Ukr. Academy of Sciences, Kiev, 252028, USSR.* The theoretical study [1] of the homogeneous stable quasi-neutral electron-hole plasma (EHP) of sufficiently high density has predicted that a stationary strongly nonequilibrium solitary state, i.e. an autosoliton (AS) can be generated there. AS appears as a stratum, perpendicular to the lines of current; it is a static or moving layer of high-temperature carriers and high electric field (E) where the concentration of quasi-neutral EHP(n) is lowered [1,2].

We report, an experimental observation of AS in photo-generated weakly-heated EHP in pure n-Ge with the EHP concentration $n \equiv p \geq 10^{14} cm^{-3}$ heat;ing field E ~50 $V\text{-}cm^{-1}$ and nitrogen lattice temperature. AS was spontaneously formed at the anode and moved along the sample as a solitary stratum (measuring about ambipolar diffusion length) of lowered EHP concentration and high electric-field strength $E \geq 800 V\text{-}cm^{-1}$. With EHP concentration growing, the field peak value increased rapidly and ran into $E \cong 3000\ V\text{-}cm^{-1}$ for $n \equiv p \equiv 10^{16}\ cm^{-3}$. The speed of AS motion is governed by the ambipolar drift rate. Parameters of the observed AS and those of EHP when AS was generated in Ge are shown to agree with the theoretical predictions.

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TuP-23 Excitation spectra of photoinjected hot carriers, A. Sergio Esperidião, *Instituto de Física, Universidade Federal da Bahia, 40210, Salvador, BA, Brasil*, Aurea R. Vasconcellos and Roberto Luzzi, *Instituto de Física, Universidade Estadual de Campinas, CP 6165; 13081 - Campinas, SP, Brasil.* We consider a double component plasma of photoinjected electrons and holes operator method in Zubarev's approach. To evidence the spectrum of elementary excitations we calculate the differential electronic Raman cross section. The latter follows from the solution of the transport equations for the (Fourier transform) density of the carriers. Besides the usual terms that appear in near equilibrium conditions, namely those associated to changes in kinetic and potential energies, terms involving laser light absorption and recombination effects are also present coupling the densities of electrons and holes. The Raman spectrum (depending on the intensity of the pumping light and the transferred wave-vector Q in the scattering event) shows four bands. The highest in frequency is the one corresponding to the out of phase joint oscillation of electrons and holes (centered around $Q = -(4\pi me^2/\varepsilon_0 m_x)^{1/2}$). With decreasing frequency, the next one is a broad band corresponding to the continuum of quasi-particle excitations. Finally, are observed two bands corresponding to scattering by excitations with linear dispersion relations: $\omega_1 = S_1 Q$ and $\omega_2 = S_2 Q$, where, approximately, $S_1 = \omega_{ple} \Lambda_{TF}$ and $S_2 = \omega_{plh} \Lambda_{FT}$, with $\omega_{ple(h)}$ the plasma frequency of the individual electron (hole) system and Λ_{FT} is the Fermi-Thomas screening length. These two novel bands are interpreted as due to scattering by *acoustic plasma waves*, which are the result of the in phase collective motion of each kind of carriers interacting through the screened part of the Coulomb interaction. These excitations should produce effects on the optical and transport properties of the system, and therefore may affect its functioning in electronic devices.

TuP-24 The hot electron kinetics in gapless semiconductors: the influence of LO-phonon interband transitions, A. V. Dmitriev, *Low Temp. Phys. Dept., Moscow State University, Moscow, 119899, USSR.* The calculations of the hot electron transport are performed for zero gap semiconductors such as n-HgTe and $Cd_xHg_{1-x}Te$ in the high electric field (E<20V/cm) at low lattice temperatures taking into account the interband LO-phonon scattering effects. Increase of the carrier concentration in the process of heating is caused by the impact ionisation whereas recombination is due to both the ehh Auger mechanism and the interband transitions with the one-LO-phonon emission. The interband LO-phonon scattering also serves as an efficient channel of the carrier energy relaxation. The influence of DA interaction on the energy relaxation is also taken into consideration which is important at the initial stage of heating (E<5V/cm). The momentum relaxation of electrons is connected with the scattering by charged impurities and by holes in the valence band The hole contribution into current is negligible because of low hole mobility. The calculations are based on the Boltzmann equation within the electron temperature approximation. The electron and hole temperatures are shown to be equal. At the low field range (E<5V/cm) the LO-phonon interaction is inactive hence the carriers heat up rapidly and their number quickly increases up to $n \sim 10^{16} cm^{-3}$. At the higher field domain (5-20V/cm) the optical scattering becomes the highly efficient channel of the carrier energy relaxation so the electron temperature increase becomes much slower. As a consequence the slope of the n(E) dependence decreases significantly. The effect of LO--phonon recombination on the carrier density is shown to be of minor importance: even for high electron temperature the Auger recombination remains the most probable interband process The results of calculations agree well with the existing experimental data [1] obtained for n-HgTe at the temperature of liquid helium.

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TuP-25 Position broadening effect in hot-electron transport, R. Bertoncini, A. M. Kriman, D. K. Ferry, *Center for Solid State Electronics Research, Arizona State University, Tempe, AZ, USA 85287-6206,* L. Reggiani, *Dipartimento di Fisica e Centro Interuniversitario di Struttura della Materia, Università di Modena, Via Campi 21 3/A, I-41100 Modena, Italy,* A. P. Jauho, *Physics Laboratory, H. C. Oersted Institute, University of Copenhagen, Universitetsparken 5, DK-2100 Copenhagen, Denmark.* We present a novel quantum effect induced by the simultaneous presence of phonon scattering and an external electric field, which produce an electron trajectory that is discontinuous along the field direction (z). Recognizing that the field breaks the symmetry of the electron system, so that the momentum along this direction is no longer a good quantum number, we use Airy transforms to treat the position dependence within a non-equilibrium Green's function approach. Based upon exact solution of the uncoupled system, we solve Dyson's equation for the single-particle retarded Green's function $G^r(k_\perp,z,z',\omega)$. The net effect of the field is to produce a discretization of the electron trajectory which can be described quantitatively using an Airy coordinate s, defined through the Airy transform

$$\hat{f}(s) = \int_{-\infty}^{\infty} f(z)\, Ai\left(\frac{z-s}{L}\right) dz$$

with $L = (\hbar^2/2meE)^{1/3}$ the usual field length, and z the real-space coordinate. This path discontinuity, which can be interpreted as a field-assisted tunneling in real space, is ultimately responsible for a broadening of the carrier position after each scattering event: A novel Monte Carlo simulation, capable of providing a quantitative description of this effect, will be proposed and discussed.

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TuP-26 Hot carrier effects in quantum-confined devices, G. J. Iafrate, U.S. *Army Electronics Technology and Devices Laboratory, Fort Monmouth, NJ,* J. B. Krieger, *City University of New York - Brooklyn College.* A novel formalism has been developed for treating Bloch electron dynamics and quantum transport in inhomogeneous electric fields of arbitrary strength and time dependence. In this formalism, the electric field is described through the use of the vector potential. This choice of gauge leads to a natural set of basis functions for describing Bloch electron dynamics; in addition, a basis set of localized, electric field-dependent Wannier functions have been established and utilized to derive a quantum "Boltzmann equation" which includes band-structure effects and explicit band-mixing transients such as an effective mass dressing and Zener tunneling. The application of this formalism to quantum transport in spatially localized inhomogeneous electric fields such as occur in problems involving tunneling through "band-engineered" tunneling barriers and impurity scattering is presented. Specific results concerning the dominant role of electron-electron scattering under hot electron conditions and spatial electron confinement for quantum-well, single-barrier, and double-barrier diodes will be discussed; particular emphasis is devoted to *potential limitations* of three-terminal operation in these types of diodes due to hot-electron/confined-electron interactions, and the *potential advantage* for field-assisted current gain in superlattice diodes. Lastly, a complete description of impact ionization is presented which includes the all-important influence of band-structure dependence on this process.

TuP-27 A broad theoretical approach to the investigation of mesoscopic electron devices, Umberto Ravaioli, *Coordinated Science Laboratory and Department of Electrical Engineering,* Fernando Sols, *Coordinated Science Laboratory and Department of Physics,* and Thomas Kerkhoven, *Department of Computer Science; University of Illinois at Urbana-Champaign, Urbana, IL 61801.* Nanofabrication technology has matured to a point where it is possible to realize mesoscopic structures with dimensions comparable to the phase coherence length of conducting electrons. This is likely to create a whole new scenario of electronic devices based on quantum wires or electron waveguides, exploiting quantum interference effects. Semi-classical theoretical approaches are inadequate to study this class of devices, and new tools based on quantum mechanics need to be developed. We have focused our attention to specific issues dealing with the realization of three terminal structures exhibiting switching behavior due to quantum interference effects. We have developed two types of numerical simulation tools: (a) a two-dimensional Green's function method, based on a tight-binding lattice, to study the transmission properties of ideal electron waveguide structures; (b) a highly efficient two-dimensional algorithm for the self-consistent solution of the coupled Poisson's and time-independent Schroedinger's equations. With the Green's functions method we have analyzed the effect of lateral stubs on the transmission probability in a quantum wire, thus achieving a transistor purely based on quantum interference. An optimization study, including structures with multiple stubs will be discussed, along with design criteria which can be derived from the method and new results obtained for other structures. The self-consistent Poisson/Schroedinger solver is used to investigate the actual subband wavefunctions and energy levels in the cross-section of a realistic quantum wire, and is essential to understand the effects of multimode propagation in the conduction channel, and in particular to identify structures where monomode propagation is possible. Simulation results will be presented for various operation temperatures. The main goal is to merge the two approaches presented to obtain flexible design tools for the realization of mesoscopic electron devices.

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TuP-28 Theory of non-linear transport in quantum waveguides J. R. Barker, M. Laughton and J. Nixon, *Nanoelectronics Research Centre, Department of Electronic and Electrical Engineering, University of Glasgow, Glasgow, G12 8QQ, United Kingdom.* The present interest in quantum ballistic electron transport in semiconductor structures has generated a requirement for accurate modelling of electron wavepacket motion in single and multiply-connected quantum waveguide structures such as the Aharonov-Bohm ring device, the lateral resonant tunnelling device and the pinched-channel or throttle device. Although powerful analytical and numerical methods exist for one-dimensional problems very little work has been reported on the 2D or 3D problems posed by the finite extent nature of the conducting channels in a low-dimensional electron waveguide. Previous studies have used Crank-Nicholson and ADI algorithms to solve the finite-differenced 2-D Schrödinger equation but the method is weakened by boundary value difficulties and requirements for very large array sizes especially for strong magnetic fields. Two methods to deal with this problem are discussed. The first is a Green function based theory for the coupled mode equations which allows phenomena such as dissipation to be investigated. It leads to a set of coupled Wigner equations. The case of a 2-D model confinement potential is investigated where $V(x,y) = V_i(x)$ for $y_{i-1} < y < y_i$ ($i=1,2,3$) and $V \rightarrow \infty$ for $y=y_0$ and $y=y_3$. It is possible to to obtain the instantaneous transverse states exactly. The model allows the investigation of ring devices, tapers and soft-walled confinement potentials for which evanescent states are important. Analytical and numerical results are presented for these structures and it is shown that slowly varying soft-walled potentials may be understood from a re-scaled hard wall model. The methodology is also used to analyse the influence of soft confinement potentials and surface fluctuation phenomena on the amplitude of driven interference devices including the Aharonov-Bohm ring device. The results are in accord with experimental observations of quite small modulation amplitudes in the guide transmission. In a second approach which is a new semi-analytical method we represent the n-D time-dependent and time-independent Schrödinger by a wavefunction defined on a finite, continuous 1-D network spanning the n-D electron waveguide. On each branch of the network the wavefunction is one-dimensional and is propagated between network nodes by a 1-D S-matrix or T-matrix determined by 1-D algorithms. The wavefunctions along different branches are matched at the nodes by a unique S-matrix which preserves local physical continuity. The network equations of motion are formally solved by a S and T sub-matrix formalism which builds in the preservation of unitarity and pseudo-unitarity. The method is intrinsically more accurate than finite-difference methods with the same mesh size. The approach is illustrated by applications to the tapered quantum waveguide or throttle where it is compared with finite-difference methods and finite mode analysis. This method is being investigated for the 3-D modelling of quantum waveguides.

TuP-29 Theory of ballistic electron transport through quantized constrictions,* Song He and S. Das Sarma, *Department of Physics, University of Maryland, College Park, Maryland 20742.* We develop a quantitative theory for electron transport through quantizing constrictions [1] in semiconductor microstructures. Our theory is based on the Kubo formula which is calculated using the recursive Green's function technique [2]. We obtain the conductance of the system from the completely ballistic (*no* impurity scattering) to the diffusive regime, showing how the quantized conductance of the ballistic transport goes over continuously to the conductance fluctuations in the diffusive regime. We study the effects of temperature, inelastic and elastic scattering, system length and width on the conductance quantization phenomenon [1]. We find the quantization to be quite fragile, being destroyed by having both too high or too low temperatures and by elastic and inelastic scattering. We show that the classical resistance addition formula is invalid for these ballistic quantum constrictions. We study in detail the quantum resonances on the conductance plateaus arising from electron wave reflection from edges and impurities, and, show how these quantum structures can be used as a diagnostic characterization tool to study the shape of these constrictions. Finally, effect of a magnetic field on the conductance quantization phenomenon is discussed.

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TuP-30 A two-dimensional hot carrier injector for electron waveguide structures, Craig S. Lent, Srinivas Sivaprakasam *Department of Electrical and Computer Engineering,* and David J. Kirkner, *Department of Civil Engineering, University of Notre Dame, Notre Dame, Indiana 46556.* Improvements in epitaxial growth techniques have made possible a large number of quantum devices which are one-dimensional in the sense that carriers are confined in only one spatial dimension. Recent advances in lithography have begun to produce structures which are quantized in two and three spatial dimensions. Of particular interest are quantum waveguide devices in which carriers are confined to narrow channels which act analogously to microwave channels. Just as the development of one-dimensional devices has been guided by the solutions of the one-dimensional Schrödinger equation, solutions of the two-dimensional Schrödinger equation will be important in guiding development for these lithographic structures.

We investigate the ballistic transport properties of a two-dimensional resonant cavity waveguide device which is used as a hot-electron injector. Electrons are confined in a channel of width d which widens to a width D in the cavity itself. An electric field is applied across the cavity resulting in ballistic injection of carriers from the cavity into the outgoing channel. The potential in the waveguide region is shown below. We calculate the current-voltage characteristic of this structure by directly solving the 2-D Schrödinger equation using the Finite Element Method. The cavity makes it possible to inject into the higher energy modes of the output channel. We discuss possible device applications and integration of such an injector with other waveguide devices.

TuP-31 Effective potential for moment-method simulation of quantum devices,* H. H. Choi, J. Zhou, N. C. Kluksdahl, A. M. Kriman and D. K. Ferry, *Center for Solid State Electronics Research, Arizona State University, Tempe, AZ, USA 85287-6206.* In the simulation of submicron devices, complete quantum descriptions are numerically intractable, and reduced descriptions are used. One such description utilizes a few low-order moments of the momentum that are defined by the Wigner distribution function. Two main difficulties occur in applying this moment method: (i) An independent calculation is required to find quantum mechanically accurate initial conditions. (ii) For a system in a mixed state, the hierarchy of time evolution equations for the moments does not close. We describe an effective potential that solves these problems. The distribution function is determined by a number of parameters equal to the number of independent moments, thus closing the hierarchy. The effective potential accurately describes barrier penetration and repulsion, as well as the broadening of the momentum distribution. Previous effective potentials, based on semiclassical approximations of the partition function, diverge in the presence of the infinite barriers used in many microstructure FET models. The new effective potential is a well-behaved functional of the real potential, has the proper asymptotic behavior near sharp potential discontinuities, and gives errors in density at the few per cent level. Like previous effective potentials, it also approaches the correct high-temperature limits. The effective potential can be determined self-consistently to take account of band-bending. We discuss its application to the MESFET and to the Resonant Tunneling Diode.

* Work supported in part by the Office of Naval Research.

TuP-32 Quantum moment balance equations and resonant tunneling structures,* H. L. Grubin and J. P. Kreskovsky, *Scientific Research Associates, Inc., P. O. Box 1058, Glastonbury, Connecticut 06033.* The application of moment balance equations to submicron and ultrasubmicron devices has provided key physical insight into the operation of these structures. A very similar approach has been taken for quantum transport. The approach is based on the fact that moment equations can be developed from a variety of representations, such as the Wigner-Boltzmann equation discussed at an earlier Hot-Carrier Conference. The key issue is the presence of mixed states. The work to be discussed consists of the first three moments of the density matrix subject to to a number of key assumptions. The equations include the presence of a quantum mechanical based density dependent potential, often referred to as the Bohm quantum potential: $Q = -(\hbar^2/2m)(\nabla^2\sqrt{p})/\sqrt{p}$. The first two moment equations have been implemented for numerical computation and include the effects of scattering. Calculations have been performed on a variety of structures, including those with moderately doped cladding layers, and asymmetric barriers. All calculations include the presence of Fermi statistics. The algorithms include self-consistency through Poisson's equation and show the presence of negative conductance, with peak-to-valley ratios that are below that predicted from the Tsu-Esaki formulation. The calculations shown the appearance of a significant amount of charge accumulation at the upstream barrier, and significant depletion at the downstream barrier. The effect of hot carriers and transients on the device operation will be discussed. *Supported by the Office of Naval Research and the Air Force Office of Scientific Research

TuP-33 A quantum description of drift velocity overshoot at high electric field in semiconductors, F. Rossi and C. Jacoboni,. *Dipartimento di Fisica, Università di Modena, Via Campi 213/A, 41100 Modena, Italy.* When transport phenomena are characterized by typical lengths of the order of the carrier coherence length, and typical times comparable with carrier relaxation times, the classical transport theory based on Boltzmann equation is not adequate for their description. In this work we discuss the quantum theory of the overshoot of the drift velocity of electrons in semiconductors, which is of great interest in device modelling. In particular in a quantum description several features become relevant:

a) The "intracollisional-field effect" reduces the efficiency of all scattering mechanisms and therefore, tends to increase the value of the drift velocity.
b) Energy nonconserving transitions, allowed at short times in a quantum scheme, act in a different way for the various mechanisms.

In the case of intravalley polar scattering, characterized by a small momentum transfer, an increase of the drift velocity overshoot may result while nonoptical phonon transitions act in the opposite direction. In the case of scattering to upper valleys in polar materials the energy threshold decreases so that the peak of the drift velocity tends to decrease.

The net result for a particular overshoot phenomenon depends on the type of semiconductor under investigation and on the external conditions.

Finally this work shows that in a quantum description the separate-valley model cannot be retained because one intervalley transition can interfere with other intervalley transitions giving rise, within this model, to ambiguities. A procedure is suggested that takes into account a single band structure in the whole Brillouin zone.

TuP-34 Impurity scattering in quantum transport simulation, C. Jacoboni, P. Menziani, and F. Rossi, *Dipartimento di Fisica, Università di Modena, Via Campi 213/A, 41100 Modena, Italy.* This work presents a particular application of the Quantum Monte Carlo method (QMC) for the solution of the Liouville-von Neumann equation, to the analysis of the effect of impurity scattering on transient transport properties of hot electrons.

Besides the well known "intracollisional-field effect" and energy nonconserving transitions, it has been found that the following features are relevant.

a) Multiple collisions take place when a new process begins while another one is not yet completed.
b) The theoretical approach shows the presence of terms which represent higher order corrections to the Fermi golden rule.
c) There exist interference phenomena of different Feynman trajectories, which give rise to "quantum corrections" and weak localization.
d) There exist quantum interferences between phonon and impurity scattering.

WA-1 Tunneling between two quantum wells: $In_{0.53}Ga_{0.47}As/InP$ vs. $GaAs/Al_{0.35}Ga_{0.65}As$, M. G. W. Alexander+, W. W. Ruhle+, R. Sauer*, W. T. Tsang†, K. Ploog+, and K. Kohler§; + *Max-Planck-Institut für Festkorperforschung, Heisenbergstr. 1, D7000 Stuttgart 80, FRG,* * *Physikalisches Institut der Universität Stuttgart, Pfaffenwaldring 57, D7000 Stuttgart 80, FRG,*† *AT&T Bell Laboratories, Murray Hill, New Jersey 07974, USA,* § *Fraunhofer-Institut für angewandte Festkorperphysik, Eckerstr. 4, D7800 Freiburg, FRG.* The tunneling of electrons and holes between double quantum wells (QWs) is investigated by time-resolved photoluminescence in the picosecond regime at liquid helium temperatures. Each CBE grown sample, out of a set of four, contains two $In_{0.53}Ga_{0.47}As$ wells with nominal widths of 6nm (QW1) and 10nm (QW2), which are separated by InP barriers of various widths (nominal 2, 4, 6, and 8nm). A strong dependence of the luminescence decay time of QW1 on barrier thickness is observed at low excitation density, where the fast decay is obviously due to tunneling of electrons from QW1 to QW2. These fast decay times correspond approximately to the tunneling times calculated from the WKB transmission coefficient of electrons through the barrier and the oscillation frequeney of the electrons in QW1.

The recombination of QW2 only shows a weak dependence on density. However, the luminescence decay times of QW1 strongly increase with increasing excitation density. Calculations will be presented and discussed to explain this effect: Electrons tunnel in the InP based system much faster than holes, since the electron effective mass and the conduction band barrier are small. This leads at high densities to the build-up of space charge [1]. This space charge has three effects: First, a resonant tunneling situation occurs in case of level alignment. Second, the barrier shape and thereby the WKB tunneling probability is changed, and third, the constraint on the number of initial and final states available for tunneling caused by Fermi-Dirac statistics is modified. The two limiting cases of high ($10^{12}cm^{-2}$) and low ($10^{8}cm^{-2}$) excitation are thus well understood. However, it is difficult to explain why the transition occurs at quite low densities.

Comparative experiments are carried out on $GaAs/Al_{0.35}Ga_{0.65}As$ double QWs. In this system, tunneling probabilities for electrons and holes are not so different. Actually, we cannot find a strong dependence of the luminescence decay of QW1 on excitation density. The differences between the two systems will be discussed in detail.

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WA-2 Transient analysis of resonant tunneling hot electron transistor (RHET), H. Ohnishi, N. Yokoyama, and A. Shibatomi, *FUJITSU LIMITED.* We performed transient analysis of the InGaAs/In(AlGa)As resonant tunneling hot electron transistor (RHET) using a time-dependent ensemble Monte Carlo method. We switched the collector-base voltage (V_{cb}) between 2V and 0V, and thus varied the collector transfer ratio. We simulated the transient characteristics of the transfer ratio and found that the transit time depends on the sweep-out or build-up times of the space charge due to L-valley electrons in the collector barrier region. Estimated transit time from V_{cb} = 2V to 0V is 1.2 ps and that from Vcb = 0V to 2V is 2 ps.

With the base to emitter voltage held constant at the emitter peak voltage, 0.75 V, V_{cb} is switched from 2V to 0V. After steady state is safely reached, Vcb is switched from 0V to 2V. Estimated transit time from V_{cb} = 2 V to 0 V is 1.2 ps and that from V_{cb} = 0V to 2V is 2 ps.

Just after Vcb is switched to 0, there are still many L-valley electrons in the collector barrier region. Band bending in the collector barrier is due to the space charge of these electrons. As they are swept out of the collector barrier, the potential profile reaches the steady state. After V_{cb} is switched to 2 V, the transfer ratio reaches the steady state only after the front of a low velocity domain of L-valley electrons reaches the collector.

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WA-3 Energy spectroscopy of electron distributions injected by a double barrier resonant tunnelling structure, M. Heiblum, U. Sivan, and M. V. Weckwerth, *IBM Research Division, T. J. Watson Research Center, Yorktown Heights, NY.* The current transport mechanism through a double barrier resonant tunnelling (DBRT) structure is in much debate. Most arguments, which rely on two terminal I-V measurements, propose that current is carried either via elastic resonant tunnelling or via sequential tunnelling involving elastic or inelastic scattering events. Since the potential speed of the DBRT device is a direct consequence of the tunnelling mechanism, a direct way to determine the transport mechanism is necessary. Trying to shed light on this very basic question we have incorporated a DBRT structure (two AlAs barriers, 4 nm wide, separated by a GaAs well, 5.6 nm wide) as the injector in a ballistic hot electron device (THETA device [1]), and performed energy spectroscopy of the injected electron distribution [2] emerging from the DBRT. From the energy width of the analyzed electron distribution and its shift as a function of the Fermi energy in the injector, we conclude that the main mechanism for current transport through our DBRT is via sequential and not resonant tunnelling. In the low biasing regime (positive differential resistance) the current is found to contain both an elastic and an inelastic component. The elastic component, which is the smaller one, vanishes as soon as the DBRT crosses over to the negative differential resistance regime. In this mode the structure operates as a single barrier injector, namely with electrons tunnelling through the second tunnelling barrier from a quasi Fermi energy established in the well.

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The work was partly supported by DARPA and administered by ONR, contract #N00014-87-C-0709.

WA-4 Tunneling and energy—relaxation of hot electrons in double—quantum—well structures, N. Sawaki,* R. Höpfel and E. Gornik *Institute of Experimental Physics, University of*

Innsbruck, A-6020 Innsbruck, Austria H Kano, *Toyota Central R&D Labs. Inc., Nagakute—cho, Aichi 480—11, Japan.* The double quantum well structure [1] is one of the basic structure for new electro—optical devices in the near future. We have investigated the carrier dynamics in this structure by picosecond luminescence spectroscopy. The samples, made by MBE, have two kinds of GaAs quantum wells of different well width (typically L_{w1} = 140 Å, L_{w2} = 60 Å) separated by a thin $Al_{0.3}Ga_{0.7}As$ barrier layer (L_b = 60 Å). The carriers were excited by femtosecond laser pulses (CPM dye laser; λ = 620 nm, pulse width 150 fs, repetition rate 100 MHz). By analysing the correlation signal of the photoluminescence intensity excited by two laser pulses [2], one of which had been given a delay time τ, the time resolved luminescence spectra from each quantum well were studied at 77 K. We obtained the tunneling time as well as the lifetime of 2D electrons as a function of the kinetic energy. The relaxation time showed a strong energy dependence. At high energies, it was as short as 13 ps, which is determined by the cooling via emission of LO phonons. If the kinetic energy was less than the LO phonon energy of GaAs (36 meV), the decay time was of the order of 80 ps, from which the relaxation time due to the emission of LA phonon was estimated as ≈ 200 ps. At the bottom of the lowest subband in the narrow quantum well, the life time was as long as 150 ps, which is attributed to the phonon—assisted tunneling time into the wide quantum well through the potential barrier (real space transfer [1]). Since the lowest level in the narrow quantum well is by 40 meV higher than that in the wide quantum well, the tunneling is assisted by the emission of LO phonons. In case of a sample, where the energy difference is 25 meV and the tunneling is assisted not by LO phonons but by LA phonons, the lifetime was as long as 300 — 500 ps. This fact shows that the LA phonon assisted tunneling is less effective to the real space transfer between quantum wells. Comparing the results with those given by Tsuchiya et al.[3], the LO phonon assisted tunneling time is of the same order of magnitude as that obtained in a double—barrier—resonant—tunneling—diode structure.

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[3] M. Tsuchiya, T. Matsusue and H. Sakaki: Phys. Rev. Lett. 59 (1987) 2356.

WA-5 Do the X point minima affect the transport properties of resonant tunneling devices? T .J. Foster, M. L. Leadbeater, E. S. Alves, L. Eaves, M. Henini and O. H. Hughes, *Department of Physics, University of Nottingham, Nottingham NG7 2RD, U.K.*, A. Celeste and J. C. Portal, *INSA, 31077 Toulouse, France and SNCI-CNRS, 38042 Grenoble, France,* D. Lancefield and A. R. Adams, *Physics Department, University of Surrey, Guildford, Surrey GU2 5XH. U.K.*, G. Hill and M. A. Pate, *Department of Electronic and Electrical Engineering, University of Sheffield, Sheffield SI 3JD, U.K.* We have used hydrostatic pressures up to 23 kbar to modify the conduction band structure of double barrier resonant tunneling devices. The heterostructures are based on the n-type $GaAs/(Al_{0.4}Ga_{0.6})As$ system with GaAs well widths of 5 nm and 120 nm. At this composition the (AlGa)As barriers are direct gap at ambient pressure. The effect of pressure is to lower the energy of the X minima relative to the Γ minimum, so that the barriers become indirect for pressures $P \geq 4$ kbar.

The 5 nm well device shows one region of negative differential conductivity (NDC), due to a single quasi-bound state of the well. The peak to valley ratio is 20 at 77 K and atmospheric pressure. This value is maintained until P ≈ 10 kbar, when the X minima of the collector barrier coincide with the energy of the electrons confined in the quasi-bound state. Above this pressure the resonant peak and associated NDC in I(V) are rapidly quenched. This is clear evidence for $\Gamma \rightarrow X$ scattering of electrons through the collector barrier.

The wide 120 nm well device exhibits 23 regions of NDC, at 4 K and atmospheric pressure, with peak to valley ratios up to 1.25. At voltages above V ≈ 450 mV, electrons arrive at the collector barrier with energies in excess of the height of the Γ potential barrier. Despite this, well-defined resonances are observed in I(V) up to V ≈ 2 V. Unlike the I(V) characteristics for the narrower well, those for the wide well device are relatively insensitive to pressure. In particular a large number of resonances with well-defined NDC are observed even at high pressures. We discuss this qualitative difference between the pressure dependences of the two devices in terms of the intervalley scattering rates and the nature of the electron states in the wells.

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WP-1 X-point tunneling in AlAs-GaAs-AlAs double barrier heterostructures,† D. Z.-Y. Ting and T. C. McGill, *Thomas J. Watson, Sr. Laboratory of Applied Physics, California Institute of Technology, Pasadena, California 91125*. The dynamics of X-point tunneling in AlAs-GaAs-AlAs double barrier heterostructures is studied with numerical simulation. The problem is formulated within the framework of the one-band Wannier orbital model [1] which allows for simultaneous descriptions of the Γ-point double barrier profile and the X-point double well profile in this heterostructure. Time dependences of the following processes are illustrated: (1) resonant tunneling of Γ-valley electron packets via the X-point quantum well states localized in the AlAs layers, (2) non-resonant tunneling of Γ-electron packets (with energy below the AlAs Γ-point barrier) through the X-point continuum states, and, (3) resonant tunneling via Γ-X mixed quantum well states localized in both the GaAs Γ-point quantum well and the AlAs X-point double quantum well. In addition, the effects of X-point tunneling on the escape times of electrons localized in the GaAs quantum wells are examined. The device implications for double barrier tunnel structures will also be discussed.

† This work is supported by the Office of Naval Research under contract No. N00014-84-K-0501.

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WP-2 A new 'inverted bistability' effect in asymmetric double barrier structures, M. L. Leadbeater, L. Eaves, M. Henini and O. H. Hughes, *Department of Physics, University of Nottingham, Nottingham NG7 2RD, U.K.*, G. Hill and M. A. Pate, *Department of Electronic and Electrical Engineering, University of Sheffield, Sheffield, U.K.* We report a new effect in the current-voltage characteristics of an asymmetric double barrier resonant tunneling device: a region of 'inverted bistability in which the off-resonant current exceeds the resonant current over a voltage range >100mV. This inverted bistability occurs in the voltage range corresponding to resonant tunneling into the second subband of the quantum well. This effect is quite distinct from the previously reported intrinsic bistability In double barrier devices [1] where the resonant current was greater than the off-resonant current. The inverted bistability reveals itself as a characteristic crossing Or the currents of the up and down voltage sweeps. The structure investigated was based on n-GaAs/(AlGa)As with a 5.7nm thick emitter barrier and a 14.1nm thick collector barrier. In the off-resonant state electrons are injected into the well with energy greater than that of the top of the collector barrier and therefore encounter only one tunnel b:barrier. The electrostatic effect arising from the large space charge buildup in the well on resonance ($n=7\times10^{11}$ cm^{-2}) maintains the collector barrier at a higher potential. Hence the electrons encounter two tunnel barriers and the current is lower. The charge buildup is enhanced by strong intersubband scattering which reduces the probability of tunneling out of the well. Magnetic field studies show that the charge in the well thermalises to form a degenerate electron gas providing direct evidence for the sequential model of tunneling. The intersubband scattering rate, and therefore the charge buildup, is modulated by Landau level effects in an applied magnetic field (B ∥ J). This produces a periodic variation in the voltage width of the bistable region as B is increased. These measurements confirm the importance of space charge effects in resonant tunneling and the relevance of the sequential tunneling model.

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WP-3 Analysis of defect-assisted tunneling in AlGaAs/GaAs resonant tunnel diodes based on low-frequency noise measurements, M. H. Weichold AND S. S. Villareal, *TEXAS A&M UNIVERSITY, DEPARTMENT OF ELECTRICAL ENGINEERING*, and R. A. Lux, *US ARMY ELECTRONICS TECHNOLOGY AND DEVICES LABORATORY*. The novel application of low frequency noise measurement techniques to Resonant Tunnel Diodes is used in order to identify conduction mechanisms in RTDs due to defect-assisted tunneling. The theory of noise measurements is studied as the basis for the appropriate modelling of the RTD noise data. Non-linear and linear algorithms are developed to model this data and tested by simulation of expected experimental results. The actual experimental set-up has a noise floor of 10 nV/$\sqrt{\text{Hz}}$. Broadband noise measurements indicate greater excess noise currents at 0.46 Volts bias than at the bias voltage corresponding to peak resonant current at 0.25 Volts. This clearly implies the activity of competing conduction mechanisms other than resonant tunneling between the conduction band and the bound quantum-well state. Three distinct trap levels are detected. The activation energies and capture cross-sections of the traps are determined from the modeled spectral content of device noise. These values are in good agreement between the forward bias and inverted bias cases. A conjecture is made as to the physical location of the traps in the RTD. This interpretation is consistent with the known bias dependence of the trap levels and the quantum well state. Moreover, this interpretation also accounts for the difference in temperature dependence between conduction band resonant tunneling which is found to be roughly temperature independent and defect-assisted tunneling which is known to be significantly temperature dependent.

WP-4 Dc and ac analysis of high current double barrier structures, O. Vanbesien and D. Lippens, *Centre hyperfrequences et semiconducteurs, UA 287 C.N.R.S Bat P4, Universite des sciences et techniques de Lille Flandres Artois, 59665 VILLENEUVE D'ASCQ Cedex, FRANCE.* Using resonant tunneling devices as high frequency oscillators implies high current densities flowing through the structure [1]. Thin barriers are required along with cladding layers and it is expected that hot electrons effects become significant. In this paper, experimental and theoretical investigations of electrical characteristics of resonant tunneling diodes in dc and ac regimes are presented. The samples used are $Al_{0.3}Ga_{0.7}As$ (5 nm) - GaAs (5 nm) - $Al_{0.3}Ga_{0.7}As$ (5 nm) with enlarged cladding layers of about 50 nm. High current densities in excess of 2×10^4 $A\cdot cm^{-2}$ are obtained with 15 nm mesa diameter diodes.

Two points will be mainly discussed:

First, we have measured the variations of J_{peak} and V_{peak} from 77K up to 400K. At this temperature, the negative differential resistance (NDR) vanishes. The experimental findings are explained on the basis of a theoretical calculation of J-V characteristics using a transfer matrix model. It is shown that the increase of J_{peak} found experimentally over the high temperature range is well depicted by the broadening of the supply function. In contrast, in the low temperature range, a slight decrease of J_{peak} at increasing temperature is noticed. We show that the accumulation layer in front of the emitter barrier, from which hot electrons tunnel, governs the temperature dependence of J_{peak}.

Second, we report impedance measurements at microwave frequencies over a wide bias range. When the device bias is adjusted in the NDR range, direct evaluation of the frequency variation of the NDR is obtained for the first time [2]. In the thermally activated tunneling process and under resonant conditions, the bias dependence of the device conductance and capacitance suffice to explain the impedance variations. This is in contrast to measurements of ref [3] for which an intrinsic self inductance of 1 nH was detected. In a first analysis, an inductive effect can be expected because the time storage of carriers in the well cause the ac current to lag behind the ac voltage. For the present structure, the intrinsic self-inductance is found negligible with respect to the parasitic bond wire (0.5 nH). The results are supported by a theoretical calculation of the time response of the structure experimentally characterized by solving the time dependent Schrödinger equation.

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WP-5 Space-charge effects and a. c. response of resonant-tunneling double-barrier diodes, F. W. Sheard and G. A. Toombs, *Department of Physics, University of Nottingham, Nottingham NG7 2RD, England.* By means of a small-signal analysis using the sequential theory of resonant tunneling, the a.c. response of a double-barrier diode is studied and expressed in terms of an equivalent circuit. Electrostatic feedback effects due to space-charge buildup in the quantum well between the tunnel barriers are included in the analysis. It is these effects which can give rise to current bistability in the static current-voltage characteristic.

For low frequencies, ≤1 MHz for typical double-barrier GaAs/(AlGa)As heterostructures, our model predicts an increase in the capacitance of the device when biased in the region of resonant tunneling. This result is a particular consequence of electrostatic feedback and is in agreement with recent experiments on an asymmetric device in which space-charge effects are emphasized. The model is generalized to high frequencies ($\omega\tau > 1$, where $1/\tau$ is the tunneling rate through emitter or collector barriers) and the frequency dependence of the real and imaginary parts of the impedance are discussed.

WP-6 Role of structure sizes in determining the frequency characteristics of the resonant tunneling diode,* N. C. Kluksdahl, A. M. Kriman, and D. K. Ferry, *Center for Solid State Electronics Research, Arizona State University, Tempe, AZ 85287-6206.* Using the Wigner function formalism, we study the effects of structural parameters on the DC I-V characteristics and on the large-signal transient response of the resonant tunneling diode. Structures of $GaAs/Al_xGa_{1-x}As$ with symmetric barriers ranging from 3 to 8 nm in thickness are studied. Such structures, with quantum barriers ranging from 3 to 8.5 nm, have been investigated experimentally by many groups. These studies (of others) show that as the barrier thickness and height are varied, the peak-to-valley ratio in the I-V curve changes. Such results are predicted by elementary models of tunneling structures, and stem directly from the changes in tunneling probabilities. For the DC studies, we show that the peak-to-valley ratio in the I-V curve corresponds to the sharpness of the resonance of the structure, which in turn depends on the barrier thicknesses. Transient switching behavior is characterized for the varying barrier thicknesses, and is compared to earlier numerical studies of the tunneling times of wave packets through resonant tunneling structures. In the numerical tunneling time studies, charge storage within the quantum well caused an increase in the tunneling time when the wave packet was centered around the resonant energy level. This storage time is proportional to the 'strength' of the barriers. We compare the tunneling times of wave packets and the cut-off frequencies of the RTD for equivalent structures. Preliminary results indicate that the primary determining factor in the cut-off frequency is the time required to charge or discharge the quantum well.

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WP-7 Large peak to valley ratios in triple barrier heterostructures, D. A. Collins, D. H. Chow, D. Z. Ting, E.T. Yu, J. R. Söderström and T. C. McGill, *T. J. Watson, Sr., Laboratory of Applied Physics, California Institute of Technology, Pasadena, California 91125.* We have studied the effect on the peak to valley current ratios of a thin AlAs barrier in the middle of an GaAs/AlAs double barrier heterostructure. The structure studied consisted of 30 Å AlAs barriers separated by a 108 Å quantum well. The addition of a 3 monolayer (ML) barrier in the middle of the GaAs well increased the peak to valley current ratios by over a factor of 6 (from 2.88:1 to 19.3:1) at 77 °K and increased the number of negative differential resistance (NDR) regions from 2 to 3. The 3 ML middle barrier caused only a slight increase in the peak current density hence the improvement in device performance was due to a decrease in the nonresonant currents. At 300 °K the peak to valley ratios were only slightly improved by the introduction of a middle barrier indicating that the middle barrier is suppressing non-thermionic currents. We have grown a series of samples and studied how the peak to valley ratios vary with middle barrier thickness. Device performance was best for the sample with the thinnest middle layer with a small degradation in performance as the barrier is thickened until a critical thickness is reached. For a barrier wider than the critical thickness there was a marked decrease in the peak to valley current ratio and peak current density and only 1 NDR region was visible.

WP-8 Effect of inelastic processes on the self-consistent potential in the resonant-tunneling diode, William R. Frensley, *Texas Instruments, P.O. Box 655936, MS 154, Dallas,Texas 75265, (214) 995-4436.* As a bias voltage is applied to a unipolar energy-barrier device such as the quantum-well resonant-tunneling diode, we expect that the potential drop will be accommodated by an electric field across the barrier region. This field must be generated by an accumulation of carriers on one side of the barrier and a depletion of carriers on the other side. Severe conceptual problems are encountered when one attempts to apply this picture to a high current density (thin tunneling barrier) resonant-tunneling diode. The formation of an accumulation layer requires inelastic processes, occurring at some finite rate, to permit the electrons to accumulate in the lower potential region. In a tunneling structure, however, these electrons can escape from the accumulation layer by a (possibly nonresonant) tunneling process. If the rate of accumulation due to inelastic scattering exceeds the rate of loss through tunneling, the picture of the potential described above holds. However, if the tunneling rate exceeds the scattering rate, the accumulation layer cannot form and the shape of the potential is determined over a much longer distance. The above-described effects are observed in self-consistent quantum-kinetic calculations. In the quantum kinetic model the statistically mixed state of conduction electrons within the device is represented by the Wigner distribution function. The Wigner function is found by solving the Liouville equation for ballistic electron motion, and the Liouville equation may be augmented by semiclassical collision terms to provide an approximate description of the inelastic scattering processes. It is found that the qualitative form of the self-consistent potential depends very much on the assumed rate of the inelastic processes. The conventional picture is obtained only when the scattering rate is taken to be unrealistically large. Lower scattering rates yield an obviously unphysical potential with a large gradient at the boundary. This indicates the need for a more sophisticated treatment of the boundary conditions which takes into account the change in electron distribution with electric field (that is, the series resistance of the contacts). The means by which this may be done will be explored.

WP-9 "InAs" mode LO phonon emission assisted tunneling in InGaAs/AlInAs double barrier structures, A. Celeste, L. A. Cury, J. C. Portal, *I.N.S.A.-C.N.R.S., Departement de Physique 31077 Toulouse,* and *S.N.C.I.-C.N.R.S., B.P.142, 38042 Grenoble Cedex,* M. Allovon, *C.N.E.T., 196 Avenue Henri Ravera, 92220 Bagneux,* D. K. Maude, L. Eaves, *Department of Physics, University of Nottingham, NG7 2RD Nottingham.* We present a magnetospectral analysis of the different scattering processes involved in the tunneling current of an MBE grown GaInAs/AlInAs double barrier diode.

At zero magnetic field, the I(V) characteristics of the sample show a replica peak attributed to inelastic tunneling of electrons from the emitter to the well involving an optical phonon emission [1,2]. In the presence of a quantizing magnetic field (B‖J) other features appear in the current-voltage characteristics that allow us to distinguish between the elastic scattering contribution to the valley current and the inelastic one.

Using a non-parabolicity energy-dependent effective mass correction, it is possible to describe the voltage drop across the active region of the structure, and thus to find the energy of the phonon involved in the inelastic process.

An "InAs" mode is found to be involved in agreement with previous studies on GaInAs/AlInAs single heterojunctions [3]. The existence of an interface mode is also discussed.

At magnetic fields where the cyclotron energy equals the phonon energy, the elastic Landau index non-conserving contribution to the tunnel current becomes bigger and the inelastic scattering contribution disappears, a change in the peaks amplitude is then observed and discussed.

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WP-10 Design, fabrication and operation of a hot electron resonant tunneling transistor, U. K. Reddy, I. Mehdi, R. K. Mains and G. I. Haddad, *Center For High-Frequency Microelectronics, EECS Building, The University of Michigan, Ann Arbor, MI 48109-2122, (313) 764-3305*. Various proposals have been made utilizing resonant tunneling structures in cooperation with other conventional transistor structures, however, in this work we report on progress towards a truly resonant tunneling transistor where the base is the very thin (<100 Å) quantum well. In order to make the fabrication of such a structure feasible various changes were made to the conventional resonant tunneling structure. Our structure employs a narrow band gap $In_{0.25}Ga_{0.75}As$ quantum well [1,2] where the first level is confined below the GaAs conduction band edge used in the emitter and collector regions, resulting in charge transfer from these regions and thus making the base highly conducting. Secondly, the electrons from the emitter tunnel resonantly through the second quasi-bound state, increasing the current density and reducing the electron scattering in the well. Finally, we employ a stepped barrier on the electron exiting side, enormously reducing device capacitance for high speed operation and also better confining the trapped charge in the quantum well, which otherwise would tunnel into the collector increasing base resistance and decreasing current gain. Device simulations demonstrating the three terminal properties of this structure will be presented. The base region is contacted by a combination of wet selective chemical etching and electrical monitoring techniques. The current-voltage characteristics of a typical device showed negative differential resistance at 300 K. Various DC characteristics of the transistor were measured and will be discussed. Details of device fabrication and various ways of improving the device electrical characteristics will be presented.

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WP-11 Investigation of the voltage at the peak position as a function of the transversal magnetic field in a double-barrier resonant tunneling current. The importance of k_y-value at low fields, L.A.Cury, A.Celeste, J. C. Portal, *INSA-CNRS F31077 Toulouse-Cedex and SNCI-CNRS F38042 Grenoble-Cedex*, E. S. Alves, M. L. Leadbeater, L. Eaves, M. Henini, O. H. Hughes, *University of Nottingham, Nottingham NG72RD*, G. Hill , M. A. Pate, *University Of Sheffield, Sheffield S13JD*. We have investigated the behavior of the voltage V_p at the peak position in a double-barrier resonant tunneling current as a function of the transversal magnetic field B. Our experimental results show a linear behavior of V_p with B for B>2T. This linear behavior has been estimated by Choi et al. (Phys. Rev. B 38, (1988), 12362) for a superlattice hetero-structure. They have stated that $V_p \cong eB^2<x>^2/2m^*$ for a limit condition $(eB<x>/\hbar>K_f$, where K_f is the Fermi wave-vector and $\langle x \rangle$ is the expectation value for the position operator.

The $Al_{0.4}Ga_{0.6}As$-GaAs double-barrier investigated by us presents a 2D EG in the low doped emitter region (2×10^{16} cm^{-3}), corresponding to a small Fermi energy. This enable us to observe the linear behavior above 2T according to statements of Choi et al.

We have calculated theoretically the resonant tunneling current considering a simple model without 2D EG in the emitter region. In contrast with the theoretical work done by Ancilotto (J. Phys. C: Solid State Phys. 21, (1988), 4657) our results show a displacement of the peak positions by increasing B, presenting a qualitative agreement with our experimental ones. In our calculations we have considered a large Fermi energy (E_f = 50meV) in the emitter region. Thus, we can only obtain a linear behavior for B>10T. Below this value the linearity is not verified and this fact reflects the action of K_y-value in the dispersion relation of where V_p.

WP-12 Resonant tunneling through magnetic edge states, F.M. Peeters*, M. Helm, P. England, J.R. Hayes, E. Colas, J.P. Harbison and L.T. Florez, *Bellcore, Red Bank, New Jersey 07701-7040*. Resonant tunneling of electrons through

AlGaAs/GaAs/AlGaAs double barrier structures is investigated for samples with differing quantum wells (300-800Å) and barrier widths (130-220Å). For weak magnetic fields several resonances are observed as function of the applied electric field. In this regime the current-voltage characteristics are dominated by tunneling into the two-dimensional density of states of the quantum well. The position of these resonances exhibit a diamagnetic shift.

In a strong magnetic field resonant tunneling is quenched, and a new set of resonances appear at low bias. These resonances are interpreted as due to tunneling between the edge states on either side of the first barrier. The edge states are the quantum mechanical analogue of the classical skipping orbits.

In a fan diagram, the two different regimes are identified. The position of the resonances in the electric limit are determined predominantly by the width of the quantum well, while in the magnetic limit, it is the width of the barrier which determines the position of the resonances.

A theoretical analysis of the results through an exact numerical solution of the Schroedinger equation confirms the above picture. Good agreement is found with the experimental position of these resonances.

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WP-13 Resonant tunneling in crossed electric and magnetic fields: a tool for investigating extreme hot electron effects, J. R. Hayes, P. England, M. Helm, J. P. Harbison, L. T. Florez and S. J. Allen, *Bellcore, Red Bank, NJ 07701-7040.* We have investigated the current/voltage characteristic of resonant tunneling structures having wide well regions (80nm). We observe in excess of 25 oscillations in the current/voltage characteristic associated with resonances in the quantum well as the structure is biased to 1.0V. With the application of modest transverse magnetic fields we see a weakening and shift of these oscillations to higher energies. In the talk we will describe a quantitative theory for explaining the phase shifts and results that can be inferred from them, however it can also be understood semi-classically.

The phase shifts result from a combination of two (related) effects. First, the straight line motion of electrons moving in an electric field is modified to a cycloidal path in a perpendicular magnetic field. Although the path length is increased, the component of the wave vector in the growth direction is reduced. This increases the bias at which the resonances are seen. Secondly, the Lorentz force on the electrons during tunneling causes them to acquire a transverse component of momentum $mv_y=eBb$, where b is the barrier thickness (this is just conservation of canonical momentum). This means that the electrons must be injected in with excess energy $mv_y^2/2$, for resonant tunneling to occur. This has the same effect, i.e. it increases the bias at which the resonances are seen. To complete the description, we must choose the classical trajectory through the tunnel barrier which has the maximum transmission coefficient, this is the symmetrical case where mv_y (left) = $-mv_y$ (right).

The quantum mechanical analysis enables us to determine the non-parabolicity at energies in excess of 1eV. In addition the results indicate that the scattering rate of hot electrons, at these high energies (in excess of 1eV) in high electric fields, is suppressed.

WP-14 A self-consistent model of magneto-tunneling,+ W. Pötz and J. Zhang, *Department of Physics, University of Illinois, Chicago, IL 60680.* Experimental verification of resonant-tunneling effects in quantum-well structures has been one of the recent highlights in semiconductor physics. Various systems, such as single-, double-, and multi-barrier structures have been investigated both experimentally and theoretically. More recently, tunneling in the presence of high magnetic fields has been investigated experimentally by several groups. Here, we present a self-consistent model to study resonant tunneling in the presence of external magnetic fields which are applied in growth direction. Stationary scattering theory is combined with an envelope-function approach and used to calculate the I-V characteristic of double barrier structures. Within our model, both carrier injection from the contacts and the effective potential is incorporated in self-consistent fashion. Scattering is implemented on a phenomenological level. With a magnetic field applied perpendicular to the interfaces, the motion parallel to the interfaces may be integrated out and the presence of a magnetic field can be implemented entirely into the carrier distribution function. This picture leads to a simple interpretation of our results which are obtained for conventional GaAs/AlGaAs double barriers. Every current peak in the I-V characteristics for B=0 is superimposed by additional structure which reflects the number of populated Landau levels. Inspection of the charge distribution within the well shows the contribution of individual Landau levels to the tunneling current. The importance of a self-consistent approach is discussed, and a comparison of our calculations with published experimental data is given.

+ This is work supported by the U.S. Office of Naval Research.

WP-15 Disorder effects on resonant tunneling in quantum-well hetero-

structures,+ Z. G. Li and W. Pötz, *Department of Physics, University of Illinois, Chicago, IL 60680.* Most calculations of resonant tunneling in quantum well structures are based on the assumption of absolutely perfect structural properties of the heterostructures. However, real systems contain flaws, such as impurities, structural defects, inhomogeneities, variations in the layer thicknesses, etc. Moreover, some experimental evidence has been found in support of resonant tunneling in heterostructures fabricated from amorphous semiconductors. Here we present results from a simple model to incorporate imperfections in the calculation of the current response of resonant-tunneling systems. The approach is based on a tight-binding model, which naturally lends itself to a discussion of disorder. Dyson's equation is used to obtain the Green's function of the disordered system, whereby the "unperturbed" system is the perfect system that contains a built-in potential step, in anticipation of the applied bias. The perturbation contains all the disorder as well as the applied potential. The Green's function of the system is calculated numerically, and a structural average is performed. The current through the system is obtained in a standard fashion from the transmission coefficient which, in turn, is related to matrix elements of the Greens function. Both diagonal and off-diagonal disorder is considered here. For simplicity, a one-dimensional model is used to give a qualitative demonstration of disorder effects for various systems. Based on this model, we discuss the influence of defects and disorder, such as present in amorphous semiconductors, on the current response of the heterostructure.

+ This is work supported by the U.S. Office of Naval Research.

WP-16 Imaging of spatio-temporal transport structures in semiconductors, U. Rau. K. Mayer. J. Parisi, J.Peinke and R.P.Huebener, *Physikalisches Institut, Lehrstuhl E. Experimentalphysik II. Universität Tübingen, D-7400 Tübingen, F.R.Germany.* In the light of the general theory of nonlinear dynamical systems, in particular of the theory of chaotic behavior. the experimental study of semiconductor transport instabilities has recovered a growing interest in recent years. Moreover, semiconductor systems have become one of the most appropriate tools to test the predictions of nonlinear theories.

The systems of p-Ge and n-GaAs presented here are based upon the avalanche breakdown at low temperatures via impact ionization of shallow impurities by hot charge carriers. The autocatalytic character of this process leads to a highly nonlinear region of the current voltage characteristic of such samples, also displaying negative differential resistance. As a consequence, these systems display structure formation as well in time as in space. i.e., spontaneous oscillations and the formation of current filaments in the homogeneous material.

By means of the technique of low-temperature scanning electron microscopy it is possible to visualize these current patterns. These images are obtained by the electron beam induced change of the sample conductance. Thus, the effect of the electron beam is a local disturbance of the transport properties of the semiconductor. This method can also be used in order to localize additional features of the system, so as characteristic response times and spontaneous oscillations. Particularly concerning the latter case the chopped electron beam can act as a local driving force, interacting with the spontaneous oscillation in a typical nonlinear way.

Thus, we are able to image both the spatial and the temporal structures and, hence, to identify the close relationship between the break-up of spatial order during current filamentation and the onset of low-dimensional temporal chaos in the current oscillations. For the interpretation of the experimental results, as well classical semiconductor theory as the tools of general nonlinear dynamics are applied.

WP-17 Complex dynamical behavior and chaos in the Hess oscillator, K. Aoki , K. Yamamoto, N. Mugibayashi, *Department of Electrical Engineering, Faculty of Engineering, Kobe University, Rokkodai, Nada, Kobe 657, Japan,* and E. Schöll, *Institut für Theoretische Physik, RWTH Aachen, Templergraben 55, 5100 Aachen, FRG.* In order to make clear the physical origin of "Hess oscillation" in modulation-doped heterostructure of GaAs/AlGaAs system, we report for the first time on the simulant aspects for the real space transfer (RST) of electrons and the related complex dynamical behaviors, based on an energy relaxation model. Besides the rate equation for the thermionic emission, we introduce; (a) energy balance equation in subsystems 1 (GaAs) and 2 (n-AlGaAs), and (b) dielectric relaxation response of electric field E (degree of freedom 4). In the hydrodynamic-like equations, energy loss rates due to polar optical phonon scattering and energy transfer rates are considered. The dynamical behaviors sensitively depend on the ratio of characteristic time constants $\gamma_1=\tau_\gamma/\tau_0$ and $\gamma_2=\tau_\gamma/\tau_\varepsilon$ (τ_γ: dielectric relaxation time, τ_0: characteristic transfer time of RST electrons from sub.1 to sub.2, τ_ε: energy relaxation time). With dc field E_0 being applied in the NDR region, spontaneous oscillation of RST carriers occurs only for $\gamma_1 \geq 1.2\, \gamma_2$ ($\tau_0 \leq \tau_\varepsilon$), which means that the cyclic motion occurs, say, due to incomplete relaxation of the transferred energy and due to fast thermionic emission. With adequate choice of parameter values (mobility ratio $\mu_1/\mu_2=40$,

μ_1=5400 cm^2/Vs, T_L=273K, ΔE_c=10kT_L for band gap difference, τ_γ=1.08×10^{-10}s, γ_1=30, γ_2=12, etc...), oscillating frequency is estimated to be ~18 GHz. For γ_1=30 and γ_2<16 (τ_γ=1.08×10^{-10}s), there appear period doubling bifurcation and chaos as a function of dc field E_0.

WP-18 Current controlled hot-electron instability in the three-terminal heterostructure device, A. Kastalsky, M. Milshtein, L. G. Shantharama, and J. Harbison *Bell Communications Research Red Bank, NJ 07701.* We observe a strongly pronounced current controlled (S-shaped) negative differential resistance (NDR) for electron flow normal to a modulation doped AlGaAs/GaAs structure having two conducting layers. The first conducting layer is a quantum well (QW) in which electrons, transferred from the top n^+ AlGaAs, form a high mobility two-dimensional channel. A 4000 Å undoped $Al_{0.5}Ga_{0.5}As$ layer separates the channel from the n^+ GaAs substrate (second conducting layer, collector). The Schottky gate on top of the n^+ AlGaAs layer controls electron density in the channel. At sufficiently high negative gate voltages V_G relative to the channel (grounded) we observe an S-shaped I-V characteristic in the gate-channel circuit with the onset of NDR varied by a positive collector voltage V_c. This effect is due to development of an avalanche in the depleted n^+ AlGaAs layer underneath the gate area. The voltage drop at the NDR in this case is ~ 20%. At the same time we observe much stronger S-shaped NDR in the gate-collector circuit with the voltage drop of ~ 10 times, efficiently controlled by the gate-to-channel bias. We show that in this circuit hot, nonequilibrium electrons, created by impact ionization in the n^+ AlGaAs, arrive at the QW and dramatically change the electron current tunneling through or emitting over the positively biased collector barrier. Conceptually, this phenomenon is close to that observed in the heterostructure diode [1] in which electron heating enhances thermionic emission over the barrier. In that diode the voltage drop at the NDR did not exceed ~ 20%. Much more pronounced NDR in our case is shown to be due to multiplication of hot electrons in the QW (i.e. in front of the collector barrier) caused by the avalanche in the top AlGaAs layer. [1] T. K. Higman, L. M. Miller, M. E. Favaro, M. A. Emanuel, K. Hess and J. J. Coleman, Appl. Phys. Lett. 53, 1623 (1988).

WP-19 Hot phonons and instabilities in GaAs/GaAlAs structures, N.Balkan, B.K.Ridley, *University of Essex, Department of Physics, Colchester,U.K.*, M.Emeney, *RSRE, St. Andrews Road, Great Malvern, U.K.*, J.Roberts, *University of Sheffield, Department of Electronics, Sheffield, U.K.*, I.Goodridge, *Allen Clark Research Center,Plessey Research, Caswell, U.K.* We report experimental observations concerning high-field parallel transport between 4K and 300K in GaAs/GaAlAs quantum-well structures comparing degenerate and non-degenerate material. Hot electron photoluminescence measurements show hot-phonon enhancement of the energy relaxation rates in degenerate material compared with that in non-degenerate material in accordance with a simple model of transport involving hot-phonon effects. The latter predicts a reduction in drift velocity at high fields compared with that in bulk material and this is observed in our specimens. Hot phonons are shown to inhibit instabilities. Non-degenerate samples exhibit current instabilities much more readily than degenerate material.In the latter the hot-phonon reduction in drift velocity will tend to inhibit NDR via real-space or intervalley transfer. In long ($l \geq$ 400μm), non-degenerate MQW samples large damped oscillations occur which may be associated with the acoustoelectric effect. In short ($l \leq$ 100 μm), non-degenerate MQW samples,and in long degenerate single and double QW systems at low temperatures continuous high-frequency oscillations with frequency approaching 1 GHz (carrier concentration dependent) are observed. The origin of these oscillations is obscure.

WP-20 Hot electrons and traps in a-SiO_2, Robert L. Kamocsai and Wolfgang Porod, *Department of Electrical and Computer Engineering, University of Notre Dame, Notre Dame, IN 46556.* In this paper, [1] we investigate the influence of traps on high field electronic transport in amorphous silicon dioxide. The Monte Carlo method is used to simulate hot electron transport with particular emphasis on trapping and detrapping events. More specifically, we incorporate impact ionization as a scattering event for both band-band and trap-band pair collisions. These processes provide conduction band electrons with a mechanism for losing some of the energy absorbed from the field, thereby helping to prevent velocity runaway in the insulator. Kane's random-k approximation [2] is used to determine the profile of these scattering rates in energy. This is different from the customary use of the ionization rate derived by Keldysh [3]. A constant trapping rate is used in the simulation where electrons in the conduction band jump into a localized trap state. For different external field strengths it is shown that a buildup of charge occurs. The polarity of this charge changes in time from negative to positive and can be explained in terms of the occupancy of the trap sites. When the traps in the band gap fill up, they become negatively charged. As electrons accelerate in the external field, they become hot and reach energies for which the ionization rates become dominant. This leads to the detrapping of electrons. Further ionization of valence band electrons leads to the presence of positively charged ions. Our Monte Carlo simulation microscopically confirms the dynamic trapping-detrapping models discussed in the literature [4] which seem to be consistent with experimental measurements of changes in the flat band voltage. Our simulations self consistently include the localized electric field variations which arise due to the presence of this charge buildup. No assumption is required to be made on the form of the ionization cross section as a function of the electric field. In summary, we find that trapping and detrapping events provide additional energy loss mechanisms for hot electrons in a-SiO_2 which help to explain the occurrence of stable electronic distributions in the pre-breakdown regime.

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WP-21 Space-charge anomalies in insulators caused by non-local impact ionization, B. K. Ridley and F. A. El-Ela, *Department of Physics, University of Essex, Colchester C04 3SQ.* The non-local nature of impact ionization is modelled using lucky-drift theory with the assumption that the relevant electric field is the average field, but that the relevant drift velocity is that associated with the local field. The carrier density relevant for impact ionization is also taken to be non-local. The model is applied to the case of a thin film insulator with Fowler-Nordheim injections of electrons at the cathode. For clarity's sake we avoid considering the excitation of holes and limit attention to the ionization of a set of occupied deep-level states present in high concentration. We show that the non-local nature of the ionization process reduces the local field markedly, resulting in a pile-up of free electrons to maintain current continuity in the rest of the film. This is contrasted to the prediction of local-impact-ionization theory, in which the field is reduced merely to that necessary to sustain a small level of ionization. Under certain circumstances space-charge striations are produced analogous to the situation in gas discharge. and for some film thicknesses a NDR occurs.

WP-22 Spontaneous oscillations and chaos in Si induced by excitonic impact ionization, H. Weman, A. Henry, and B. Monemar *Department of Physics and Measurement Technology, Linköping University, S-581 83 Linköping, Sweden.* We have observed spontaneous current oscillations leading to chaos in boron doped Cz-Si under optical excitation at liquid helium temperatures. The silicon samples have been annealed at 450 °C at 150 hours to contain thermal donor complexes in a concentration of about $10^{16}/cm^3$. The oscillations start at a certain critical electric field, where the impact ionization of excitons by hot free carriers set in. The current-voltage characteristic shows a highly nonlinear behaviour with a negative differential resistance. Near the breakdown region, which is close to 150 V/cm at 2 K, the current oscillates between a few mA to some hundred mA in pulses of less than a microsecond at a frequency of around 10 kHz, critically dependent on the external parameters like the applied voltage, temperature or laser excitation intensity. In the post-breakdown region we observe more slowly varying current oscillations in the millisecond range, which eventually lead to a chaotic behaviour. Without the optical excitation no oscillations are observed and the current is in the microampere range until the electrical shallow impurity impact ionization appears at about 500 V/cm. The physical mechanism causing these oscillations is suggested to be a critical balance between the impact ionization- and capture-rates of the thermal donor bound excitons. This is in analogy with the current oscillations in e.9. p-Ge near the breakdown field caused by impurity impact ionization as was recently suggested by Schöll et al. [1]. Oscillations can then appear when the impact ionization is coupled with dielectric relaxation of the electric field or the energy relaxation of the ionized hot carriers.

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WP-23 Impact ionization breakdown in p-Germanium samples with very short contact distances, W. Clauss, J. Peinke, J. Parisi and R. P. Huebener, *Physikalisches Institut, Lehrstuhl Experimentalphysik II, Universität Tübingen, D-7400 Tübingen, F.R.G.* Previous investigations on homogeneously doped p-Ge at low temperatures have shown that the electrical avalanche breakdown is caused by impact ionization of shallow acceptor levels. Just in the breakdown regime the current density displays an inhomogeneous distribution in space and time: filaments of high local current density are formed while the total current produces strong, self-sustaining oscillations, which can be highly regular as well as extremely chaotic. Both the oscillatory behavior and the integral current voltage characteristic (CVC) can be influenced very sensitivity via an external magnetic field. In order to get more insight into the physical mechanism of the semiconductor breakdown and the corresponding oscillations we have investigated a series of samples with different contact distances, ranging from 500 μm down to values of 10 μm. The contacts were fabricated by means of ion implantation. As an important result we have found that the magnetic field dependence of the CVC is significantly changed at contact distances below 200 μm. Also the breakdown electrical field is raised to higher values. These deviations from the general behavior of samples with long contact distances led to estimates of the relevant characteristic length scales involved. Spontaneous oscillations were found over the whole range of contact distances. As the distance is lowered, however, the variety of possible oscillation modes becomes apparently smaller and the form of the oscillations is less complex. From the experimental results, particularly those obtained from miniaturized sample geometries, we can extract interesting new statements concerning the driving mechanism of these "elementary" oscillations. We suspect that there exists a mutual interplay between the adjacent sample regions of bulk semiconductor breakdown at one hand and the ohmic contact regions at the other hand.

WP-24 Resonan. impact ionization in bismuth-antimony semiconductors at quantizing magnetic fields, E. V. Bogdanov, *Moscow State University, Moscow USSR.* A number of resonances have been observed experimentally in the recombination probabilities of nonequilibrium carriers in narrow gap semiconductors in quantizing magnetic fields [1]. These resonances are observed in magnetic fields for which the distance between the Landau levels is equal to the characteristic recombination energy. Since many of the processes which determine recombination – in particular, Auger transitions – can also go in the opposite direction it is possible to find resonances in the rate of carrier generation in quantizing magnetic fields [2].

In this paper measurements of the conductivity and the rate of impact ionization in $Bi_{1-x}Sb_x$ semiconductors ($0.09 \leq x \leq 0.167$) in a longitudinal magnetic field up to 40 kOe at 4.2 K are reported. In weak electric fields carrier concentration and mobility in the alloys are equal to 10^{14} to $2\times10^{15}cm^{-3}$ and 2×10^4 to 6×10^6 $cm^2/(V\text{-}sec)$ consequently. Measurements were carried out by nanosecond pulse techniques [3]. Square voltage pulses with a rise time less than 1 ns were produced by mercury-relay pulse generator.

The impact ionization strength g in $Bi_{0.86}Sb_{0.14}$ has resonances at magnetic fields H= 10 and 21 kOe which do not depend on the strength of the electric field. At the same values of the magnetic field maxima of the current I (the conductivity) are observed if electric fields are higher than the threshold for breakdown.

Similar results were obtained for all the samples studied. The magnetic fields H_N at which the resonances are observed increase with increasing gap width ε_g. The dependences of H_N on the gap width and on the angle of the magnetic field orientation can be satisfactorily described if resonances are connected with the increase of impact ionization probability due to vertical Auger transitions [4] which can take place in quantizing magnetic fields under the condition:

$$\varepsilon_{N,s} - \varepsilon_{0^-} = \varepsilon_g ,$$

where $\varepsilon_{N,s}$ and ε_{0^-} are the energies of the N,s Landau level and the lowest Landau level.

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WP-25 Instabilities and negative magnetoresistance in $Hg_{1-x}Cd_xTe$ semiconductors at avalanche breakdown, E. V. Bogdanov, *Moscow State University, Moscow, USSR.* The results of experimental investigation of the current-voltage characteristics (CVC) and current instabilities in n-type $Hg_{1-x}Cd_xTe$ ($0.18 \leq x \leq 0.25$) semiconductors in the presence of magnetic field at 4.2 K are presented. Nanosecond pulse technique has been used. The alloys studied have an electron concentration 10^{14}-10^{15} cm^{-3} and mobility 10^4-10^5 $cm^2/(V*s)$ at weak electric fields.

In typical CVC and current I pulses measured at fixed-voltage condition in the transverse magnetic field H, negative magnetoresistance (NMR) is observed in the beginning range of the avalanche breakdown. NMR is connected with the intensification of impact ionization: the steepness of the initial part of current pulses, which is determined by impact-ionization rate, is maximum just at H=1 kOe. This effect and the suppression of the breakdown by larger magnetic fields can be explained with the theory of transverse breakdown [1]. Absence of NMR at short thick samples where Hall electric field is small and characteristic dependence of the magnetic field at which maximum impact-ionization rate is observed on the angle between the magnetic field and the direction of the current confirm the role of Hall electric field in the phenomenon discussed. At H<1 kOe rapid decrease of the stationary value of current can be explained, probably, by magnetoconcentration effect [2]. Note that the stationary current is set more rapidly than at H=0 and the time of rise is almost equal to the time t of ambipolar drift of an electron-hole plasma to the surface of a sample.

NMR is observed in $Hg_{1-x}Cd_xTe$ alloys at longitudinal magnetic fields too. But in this case the electric field E of the beginning of the breakdown increases and NMR corresponds to the range of larger currents for which steepness of CVC decreases and which is called the range of anomalous resistance. This phenomenon is connected with pinching. It is confirmed by the fulfillment of Bennet criterion for so large currents and the dynamics of electric field E studied at given-current conditions: after the decrease of the resistance, which is connected with the generation of electron-hole plasma under avalanche breakdown, the increase of it takes place as a result of intensification of scattering and recombination of current carriers at plasma pinching.

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ThA-1 Very highly energy-resolved ballistic electron spectroscopy in a device capable of multi-state logic, S. J. Bending, A. J. Peck, K. v. Klitzing, *Max Planck Institut für Festkörperforschung, Postfach 800665 D-7000 Stuttgart 80, West Germany, P.Guéret and H.P.Meier, IBM Züricn Research Laboratory, CH-8803 Rüschlikon, Switzerland.* A novel hot electron transistor has been realised by incorporating a narrow quantum well (QW) into the collector barrier of a standard THETA device. It is demonstrated that up to 2% of the injected current is able to tunnel resonantly through the single subband in the QW. Plots of dI_C/dV_{CB} versus V_{CB} in this regime are a measure of the incident electron beam modulated by the voltage-dependent transmission coefficient of the QW, $T(V_{CB})$. $T(V_{CB})$ is very strongly peaked when the QW is in 'Flat-band' (V_{CB}=O), and results in a strong single-peaked resonance when electrons are injected at the subband energy (E_0), a double-peaked structure for higher injection energies, and a broad single peak for lower injection energies. It is shown that a plot of $dI_C/dV_{CB} + I_E$ versus V_{BE} when the QW is in 'flat-band' yields a very highly energy-resolved measure of the incident electron distribution. Furthermore, it is demonstrated that the injected electron beam can be 'tuned' into resonance by application of a perpendicular magnetic field when the injection energy is greater than E_0. Such a structure is the predecessor of a device capable of multi-state logic or an ultra-fast oscillator. A detailed study of the physics of resonant/sequential tunneling with the transistor is also planned.

ThA-2 Optical analysis of real space hot electron distributions in heterolayers, M. Inoue, R. Sakamoto and K. Akai, *Osaka Institute of Technology, Department of Electrical Engineering, Ohmiya 5-16-1, Asahi-ku, Osaka 535, Japan.* Developments in thin film growth and device fabrication have enabled us to provide new transport problems in various types of heterolayers. Hot electrons in heterolayers have been widely studied for their superior transport characteristics and unique two-dimensional effects. Mobility enhancement in a modulation-doped structure has been studied from electrical and ultrafast optical experiments. Under applied high electric fields, recombination spectra of 2D hot electrons have been also studied to elucidate unique transport properties in heterolayers. Since electrons heated in quantum wells by applied fields can move across the hetero-interface counteracting confinement in a quantum well, hot electron distributions become far away from equilibrium. These real space electron distributions are interesting from both a physics and a device point of view.

In the present study, we have analyzed recombination spectra of hot electrons in GaAs/AlGaAs and other heterolayers heated under pulsed high electric fields. Hot electron distributions in both GaAs well layers and AlGaAs barrier layers are quantitatively compared with the theoretical distributions in the real space. The marked field-dependent modulation of photoluminescence spectra from the both layers has been observed to provide direct evidence of dominant real space transfer of hot electrons. From these experimental and theoretical analysis of high field dependences of the spectra, unique hot electron transport properties are discussed, which will also propose high speed devices from the viewpoint of "band engineering".

ThA-3 New features of real-space hot-electron transfer in the NERFET, A. Kastalsky, L. G. Shantharama, M. Milshtein and J. Harbison, Bell Communications Research, Red Bank, NJ 07701. We present results of studying real-space hot-electron transfer in the AlGaAs/GaAs modulation doped negative resistance field effect transistor (MD-NERFET). In this device electrons in the high mobility channel (heterojunction interface or quantum well) heated by a lateral source-drain voltage (V_D) are capable of transferring over the barrier (AlGaAs layer) into the positively biased collector (n^+ GaAs layer). Development of hot-electron collector current results in a strongly pronounced negative differential resistance (NDR) in the source-drain circuit controlled by the collector voltage V_c [1]. We analyze hot-electron transfer in the MD-NERFET in which the electrons in the GaAs quantum well are provided by the top n^+ AlGaAs layer. We compare the results obtained with those of the undoped heterostructure NERFET (UH-NERFET) [2]. We show that hot-electron transfer to the collector in the MD-NERFET is impeded by a strong electron diversion to the low mobility top n^+ AlGaAs layer. As a result, a pronounced collector current arises only when the NDR occurs and a high-field domain is formed between the source and the drain, this domain being a source of hot electrons for real-space transfer. This is in contrast to the data for the UH-NERFET in which efficient real-space transfer begins prior to the NDR [2]. In the MD-NERFET the onset of the NDR is controlled by both V_D and V_c and shifts to a higher V_D as V_c increases. This feature gives rise to a strongly pronounced NDR in the collector, I_c—V_c characteristic, controlled by the drain voltage, with a peak-to-valley ratio of ~ 20. In the source-drain circuit of the MD-NERFET with a thinned n^+ AlGaAs layer (to eliminate a parallel conductance) we observe two distinct current peaks and NDR drops accompanied by two sharp steps in the collector current as we vary V_D at fixed V_c This is clear evidence for hot-electron transfer to the n^+ AlGaAs (at the first NDR drop) and final electron transfer to the collector (at the second NDR drop).

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ThP-1 Ballistic hot electron transport in n-$Al_{0.4}Ga_{0.6}As$/GaAs double barriers with wide wells, E.S. Alves, M.L. Leadbeater, M. Henini. L. Eaves, O. Hughes *Physics Department, University of Nottingham, Nottingham NG7 2RD, U.K.* This paper addresses the question "How wide can you make the quantum well of a double barrier tunneling device and still see well defined resonant structures in the I(V) characteristics ?". We have fabricated and investigated a series of double barrier structures based on n-$Al_{0.4}Ga_{0.6}As$/GaAs with barrier widths of 5.6 nm and well widths (w) varying from 20 to 240 nm. At room temperature well defined peaks in the differential conductance dI/dV can be observed for w up to 120 nm. At 4 K even a 180 nm wide well shows clear resonant structure in dI/dV. Our analysis of the I(V) characteristics of the devices provides a model for estimating the ballistic mean free path of hot electrons at energies up to ~ 1 eV above the Γ conduction band edge. The low temperature measurements allow us to demonstrate a quantum interference effect which shows up as a beating pattern in the amplitude of the differential conductance. Calculations of the transmission coefficient by the transfer matrix method using an Airy function approach show that the beating is due to a quantum effect frequently described in student texts, namely that maxima occur in the transmission coefficient of a barrier when its width equals an integral or half-integral number of de Broglie wavelengths.

ThP-2 Lateral space-charge effects on ballistic electron transport across graded heterojunctions, S. Weinzierl and J. P. Krusius, *School of Electrical Engineering, Cornell University, Ithaca, NY.* The launching of ballistic electrons [1] across graded heterostructures results in highly non-equilibrium transport as the energy-band discontinuity at the heterojunction is converted into kinetic energy. Previous one-dimensional studies of launching in heterojunction devices focused on the injection process, rather than microscopic details which affect the efficiency of launching (see e.g., [2]). In a more recent one-dimensional study, it was found that the heterojunction space charge significantly affects the electron injection process at graded heterojunctions [3]. In this work, we explore the effects of two-dimensional space charge phenomena on hot electron transport across heterostructure launchers.

The generic heterostructure launcher has a graded $Al_xGa_{1-x}As$ region and an abrupt AlGaAs/GaAs heterojunction. The structure of the launcher in this study has been derived from the cross section of a typical heterojunction vertical field effect transistor. The launcher consists of a 125nm-long N^+ doped AlGaAs layer with a 75nm-long graded region (x = 0 to 0.22), followed by 100 nm of N^+ doped AlGaAs layer with a constant Al fraction of x=0.22, and terminated by an N^- GaAs region. Transport across the heterojunction has been explored using a self-consistent two-dimensional ensemble Monte-Carlo particle simulation method. Band edges, carrier concentrations, electric fields, average velocities, and distribution functions as a function of position have been calculated. Space charges at the heterojunction have been influenced by two 200nm-long lateral reverse biased Schottky gate electrodes placed on both sides of the device structure either 100 nm downstream from the heterojunction (case 1) or symetrically on the heterojunction (case 2). For typical applied voltages (1 V across the 1.2μm-long device in the direction of the current flow, and -1.1 V total band bending at the lateral gate electrodes), the following observations are made. For case 1, there is substantial space charge accumulation at the heterojunction followed by the usual depletion in the N^- GaAs drift region. A potential well 0.1 eV to 0.3 eV deep and a spike in the Γ-valley occupation are formed at the heterojunction on the GaAs side. The peak in the spatial distribution of the drift velocity occurs 0.2 μm downstream from the heterojunction, with peak velocities of 9×10^6 cm/s observed. In case 2, no space charge accumulation at the heterojunction is observed, and peak drift velocities 40% greater than those in case 1 are achieved immediately after the heterojunction and are sustained throughout the following drift region. The total current throughput of the device is thus enhanced by more than a factor of two.

These results show that local space charges control non-equilibrium transport across heterojunctions in multi-dimensional device structures. Space charges arise from nonlocal phenomena via current continuity and Poisson's equation and thus determine dynamic variables from band edges to distribution functions. It is imperative to include multidimensional space charge phenomena into all realistic studies of transport in inhomogeneous device structures.

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ThP-3 Hot electron injection in millimeter wave Gunn diodes, N. R. Couch, M. J. Kelly, H. Spooner,* and T. M. Kerr, *GEC Hirst Res. Centre, East Lane, Wembley, Middlesex HA9 7PP, UK.* The use of graded aluminium composition layers of AlGaAs alloys, together with a modified doping profile at the beginning of the drift region, has resulted in 94 GHz GaAs-based heterojunction Gunn diodes with room temperature power exceeding 70mW, and a performance whose temperature dependence between -40C and +80C is only a quarter of that achievable in homojunction GaAs Gunn diodes at the same frequency. The output power versus applied bias is high and relatively constant over a much wider of bias when heterojunctions are used, which greatly assists circuit designers. The relevant physics of hot electron injection into the drift region of a Gunn diode is described, and we explain how this injection results in improved device performance. Extensive simulation studies complement the practical device design, and interpretation of device results. We outline further possible improvements and the problems that remain to be solved.

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ThP-4 Effective velocity-field characteristics in submicron GaAs MESFET's including near ballistic transport, Yoshinori YAMADA, *Department of Electrical Engineering and Computer Sciences, Kumamoto University, Kumamoto 860, JAPAN.* The velocity-field(V-F) characteristics under the gate of the 0.25 μm and 0.5 μm gate GaAs MESFETs have been evaluated during the steady state and the switching operation(OFF → ON) using the particle simulator with an ensemble Monte Carlo technique.

In the steady state, the electron transport in the low-field region should be expressed by the effective mobility(μ_{eff}) including the near ballistic transport, not by the bulk one. The μ_{eff} is rather small compared with the bulk one, and decreases due to the inertia of electrons as the drain voltage or the average gradient of the distribution of electric field increases. We have derived a simple analytical expression for μ_{eff} using relaxation time approximation(RTA). It agrees with our simulations. The expression of μ_{eff} is very useful for analytical modeling of the device. The dependence of μ_{eff} on V_D should be taken into account in experimental determination of the saturation velocity. The use of μ_{eff} may estimate a larger saturation velocity. During the switching operation, the time-dependent V-F characteristics have been observed, which are shown in Fig. 6. The dependence are basically due to the time variation of the valley populations. But the time dependence is not so simple as Elshner et al. considered under uniform electric field and carrier density. The characteristics show a S-like curve instantaneously and the velocity peak does not monotonically decrease to the ON steady state one. These properties were not considered in the model presented by Elshner et al. By the way we can show the current responses calculated using 300,000 particles in which the numerical noise is well suppressed.

ThP-5 Hydrodynamic hot-electron transport simulations of enhanced transit times in submicron N^+-N^--P^+-N^--N^+ GaAs device structures, D.L. Woolard, R.J. Trew, M.A. Littlejohn *Electrical and Computer Engineering Department, North Carolina State University, Raleigh, North Carolina 27695-7911,* and C.T. Kelley, *Department of Mathematics, North Carolina State University, Raleigh, North Carolina 27695-8205.* A new hydrodynamic hot electron transport model is used to study electron transport through a submicron N^+-N^--P^+-N^--N^+ GaAs structure to investigate the conditions under which enhanced electron transit times due to velocity overshoot effects are observed. The model is based upon the semiclassical "hydrodynamic" conservation equations for the average carrier density, momentum, and energy. The model includes particle relaxation times, momentum relaxation times, energy relaxation times, electron temperature tensors and heat flow vectors as a function of average carrier energy for the Γ, X and L valleys of GaAs. Transport parameters are calculated using the Monte Carlo method in conjunction with the ergodic principle applied directly to the integral definitions for the parameters. Therefore, the model includes nonequilibrium transport effects such as velocity overshoot and nonuniform average electron energy.

In this paper, we present the results of a transport optimization study of a N^+-N^--P^+-N^--N^+-device structure. The new model is utilized in this study to determine the effect of varying the position and magnitude of the p spike on the electron transit times through the entire device structure. Features of this study on the device structure include: (1) The inclusion of self-consistent potentials. (2) The inclusion of the effects of realistic boundary conditions on the device's active region The multipoint non-linear boundary value problem that results from applying the transport model to the device structure is solved using an efficient local nonlinear solver combined with a perturbation-in-doping based continuation method. The electron transport results are compared to results from both a drift-diffusion model approach and a self-consistent ensemble Monte Carlo analysis of the same GaAs device structure.

Since the new model is analytic it can easily be applied in the investigation of practical submicron device structures operating under realistic conditions. Also, this model promises to be much faster than the more traditional Monte Carlo approach in generating solutions to complex transport problems.

ThP-6 Monte Carlo simulation of AlGaAs/GaAs heterostructure MIS-like FET accounting for the gate current, R.Fauquembergue, J.L. Thobel, K.Bellahsni, P. Bourel, M. Pernisek, *CENTRE HYPER-FREQUENCES ET SEMI CONDUCTEURS UA CNRS 287 UNIVERSITE DES SCIENCES ET TECHNIQUES DE LILLE FLANDRES ARTOIS 59655 VILLENEUVE D'ASCQ CEDEX.* It has been shown that heterostructure MIS-like FET under high gate bias exhibits large gate current and this may lead to negative differential resistance (NDR) effect which can be exploited for various applications. The purpose of this work is to study the physical phenomena inducing gate current, to precise how they occur in a realistic submicron device and to discuss their dependance on bias voltages and device's geometry. For this purpose we used an ensemble Monte Carlo method associated with a 2D Poisson solver. We studied devices with various geometries and calculated physical quantities of interest (electric field mapping, carrier's energy distribution...) and also electrical characteristics (current and related parameters).

As expected, the gate current resulting from the real-space-transfer across the heterojunction depends strongly on the transverse electric field and on electron's energy which is closely related to the parallel electric field. The repartition of these fields shows a complex dependance on drain and gate bias and is strongly influenced by the 2D device's geometry. We have studied the influence of biasing conditions on the carrier's behaviour with, for example,calculations of the carriers distribution in the device clearly showing the real-space-transfer effect near the source and drain edges of the gate giving rise to the gate current. Another interesting feature is the strong dependence of gate current on source-gate spacing L_{sg} (especially when V_{ds} is well below V_{gs}). Simulations show that L_{sg} has a noticeable influence on the magnitude of the NDR effect which is reduced when L increases. We also studied the influence of other technological parameters such as gate length, AlGaAs layer thickness... and all the results will be presented and discussed.

ThP-7 Two-dimensional simulation of sub-µm GaAs MESFET's with ion-implanted doping, Y. K. Feng and K. Schünemann, *Technische Universität Hamburg-Harburg, Arbeitsbereich Hochfrequenztechnik, Postfach 90 14 03, D-2100 Hamburg 90, West-Germany.* Because of problems in the numerical simulation of channels with doping concentrations above 2×10^{17} cm^{-3}, the properties of sub-µm FET's with ion-implanted doping profiles have not yet been extensively investigated. All published simulations are performed for lower channel doping. In this work, such GaAs MESFET's (surface doping concentration up to 5×10^{17} cm^{-3}) are analyzed by using a full dynamic transport model which consists of the particle conservation equation, the time-dependent momentum conservation equation, and the energy conservation equation. The particle conservation equation is solved based on a half-point finite difference expansion in order to avoid large errors that could arise in the evaluation of the current densities. The latter ar e discretized by a modified Scharfetter-Gummel technique. In order to overcome the time step limitations of the explicit numerical schemes, a partially implicit scheme which is similar to the Crank-Nichoison method has been used. The rational Runge-Kutta method is used to solve the time-dependent momentum conservation equation, while the energy conservation equation is solved by a straight-forward time integration scheme assuming the current density and the energy gradient to be known. Important results obtained by this work are:

- 1.) The simulated I_{DS}/V_{DS} characteristics of two FET's with 0.4 µm planegate and with 1.0 µm recess-gate, respectively, are in good agreement with experiments.
- 2.) The calculated I_{DS} of a 0.4 µm gate-length GaAs MESFET with ion-implanted doping is higher by about 70 % than with uniform doping.
- 3.) Devices with ion-implanted doping show significant velocity overshoot effects.

ThP-8 Interface state generation mechanism in n-MOSFET's, N. Yasuda, H. Nakamura, K. Taniguchi and C. Hamaguchi, *Department of Electronic Engineering, Osaka University, Suita City, Osaka 565 Japan.* Hot-carrier injection into the gate oxide in small geometry MOSFET's results in interface state generation, where holes are known to be more efficient than electrons. It is pointed out that there is a possibility of hole injection from the anode when electrons are injected into the gate oxide. In order to clarify whether electron or hole is responsible for the interface state generation, we have measured the oxide field dependence of the interface state generation during the substrate hot-electron injection. The samples used in this study are n-channel MOSFET's with a 20 nm gate oxide layer, which are fabricated in a p-well with the acceptor concentration of $2\times10^{16}cm^{-3}$. The electron injection is carried out at several gate voltages with a constant p-well voltage. Interface state density is measured intermittently during the electron injection with the charge-pumping technique. The generated interface state density at a small amount of injection shows a power dependence of the electron density, using the following relation

$$\Delta N_{SS} = A\, N_{inj}^{\,n}$$

where the exponent is 0.5 at the gate voltage below 7 V, and 1.0 at the gate voltage above it. The exponent of 0.5 indicates that the interface state generation is limited by diffusion, as pointed out by Hu et al. The interface state generation with the exponent of 1.0 is explained in terms of the surface plasmon model. We have also investigated the energy location of the generated interface states from a change in the Id-V characteristics of a MOSFET. The interface states generated at the gate voltage below 7 V are located close to the conduction band edge, while those generated at the gate voltage above 7 V have the energy level near the midgap, besides at the band edge.

ThP-9 Light emission from hot carriers in FET-devices, M. Herzog and F. Koch, *Physik-Department, Tech. Univ. München, 8046 Garching, FRG,* and C. Moglestue and J. Rosenzweig, *Institut f. Angewandte Festkörperphysik, 7800 Freiburg, FRG.* Carriers heated by the source-drain electric field in field-effect transistor structures emit light in a broad spectral range. The light is characteristic of dynamic processes in the FET channel. In particular, band-gap radiation is a signature of minority carrier generation and subsequent recombination.

In previous experiments we have studied spectrally resolved emission from si MOS-devices between 0.8 and 1.5 eV, including the band-gap feature[1]. More recent work has concentrated on monitoring changes in the spectrum with time-dependent degradation in the Si device and on relating the light to electrical parameters. A major instrumental improvement has been the use of a Fourier Transform Spectrometer for the spectral measurements of the low level signals.

We report here on the work involving GaAs MESFETs and using the Fourier Transform Spectrometer to cover both visible and infrared emissions. The MESFET devices used to date have shown spatially inhomogeneous emission, with visible light initially emerging from filaments in the drain region. With further increase of the drain voltage these filaments merge to cover the entire width of the drain electrode.

We relate the emission to electrical parameters and Monte-Carlo calculations of the MES-devices. The calculations predict the rate and spatial location of electron-hole generation processes-in the device and can be compared directly with the measured emission.

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ThB-1 Femtosecond electron and hole thermalisation in AlGaAs, R.A. Taylor C.W.W. Bradley and J.F. Ryan *The Clarendon Laboratory, University of Oxford, Oxford, UK.* Femtosecond optical absorption spectra of $Ga_{1-x}Al_xAs$ reveal discrete optical phonon emission by electrons and rapid thermalisation of electrons and holes to a *two-temperature* carrier distribution. We have employed the pump/probe technique using an amplified colliding pulse modelocked dye laser and femtosecond continuum, with a time resolution of 100fs. By suitable choice of x we optically generated electrons with energy $E_e \sim 2E_{LO}$ and holes with energy $E_h \ll E_{LO}$. The carrier density generated is ~ 5×10^{17} cm^{-3} per pulse. Energy relaxation of electrons by LO phonon emission is observed at early times, well before thermalisation is achieved. By monitoring the filling of low-energy states close to the band edge we find that thermal distributions are established after t ~ 600fs. At this time the hole temperature is T_h = 55K ($\approx 2E_h/3k_B$), which indicates that hole energy relaxation is relatively slow. The electron temperature at this time is T_e = 430K, which shows that electrons lose almost half of their initial energy to the lattice during thermalisation. For t ~ 600fs the hole temperature is observed to increase, due to interaction with the electrons, and the electrons cool. At t ~ 7ps we observe the electrons and holes to come to equilibrium, i.e. a *single-temperature* carrier distribution is established, with a temperature of 110K. At later times the carriers cool in the manner observed previously in time-resolved photoluminescence experiments.

ThB-2 Fast, alloy-disorder-induced intervalley scattering in $Al_xGa_{1-x}As$, H.

Kalt, W.W. Rühle, and K. Reimann, *Max-Planck-Institut für Festkörperphysik Heisenbergstr. 1, D-7000 Stuttgart, FRG.* Time-resolved photoluminescence spectroscopy in the ps-regime is carried out on $Al_xGa_{1-x}As$ epitaxial layers at ~6K. We investigate a situation where the Γ and X valleys are separated by energies less than or close to the zone-boundary phonon energies, in order to distinguish between phonon-assisted and phonon-free intervalley scattering. First, we select a sample with the Γ and X conduction band minima almost exactly aligned. The sample still has a direct gap at resonant ($h\nu_{exc} = E_g$) excitation as revealed by a fast decay of luminescence. The bandstructure becomes indirect and luminescence decay becomes long for $h\nu_{exc} > E_g$, since the X minima are then populated and renormalize stronger than Γ. A flash-like, lifetime-broadened luminescence from the Γ minimum during the laser pulse reveals a fast intervalley scattering, although intervalley transfer from Γ to X cannot occur with phonons. We obtain from the linewidth a lower limit of 26 - 68fs for the transition time from Γ to X depending on the Γ - X separation which increases with density. Second, hydrostatic pressure is applied to a direct $Al_{0.36}Ga_{0.64}As$ sample to cross the Γ and X minima. A scenario as above occurs when Γ and X line up. The sample is already clearly indirect at 8.0 kbar and we observe a strong, long lived zero-phonon line and two weak GaAs- and AlAs-like LO-phonon replica. The strong zero-phonon line provides further evidence for fast intervalley transitions from X to virtual states at Γ without phonon participation. Alloy-disorder-induced scattering between Γ and X thus proves to be very efficient, although not yet taken into account as fast intervalley-transfer mechanism even in electrical-transport measurements.

ThB-3 Quantitative measurements of intervalley and carrier-carrier scattering in GaAs with hot (e,A^0) luminescence, J. A. Kash, R. G. Ulbrich*, and J. C. Tsang, *IBM Research Division, T. J. Watson Research Center, Yorktown Heights, New York 10598 USA.* We have used photoluminescence from nonequilibrium electrons recombining at neutral acceptors to quantitatively measure hot electron kinetics in GaAs. Values have been obtained for intervalley scattering rates as a function of electron kinetic energy and the scattering rate of a single nonequilibrium electron in the presence of a sea of thermalized electrons. These measurements show the power of this new probe of non-equilibrium carrier relaxation in direct gap semiconductors.

For low injected carrier densities, the hot (e,A^0) luminescence consists of a series of peaks spaced by the LO phonon energy which directly shows the cascade nature of polar phonon emission [1]. These peaks provide an internal clock whose period is the LO phonon emission time, 180 fsec in GaAs. Because of this "clock", and because the emission is independent of the photoinjected holes, our analysis of the data requires no complicated modeling to obtain the scattering rates. In addition, observation of the emission enables us to determine and thereby control which of the various hot carrier interactions are important, so that we can study each in isolation. As a simple example, the linewidth of the peaks at emission energies slightly above the bandgap is consistent with the theoretical polar emission rate.

Measurement of the intervalley scattering rate [2] is derived from the intensities of the various peaks seen in the hot (e,A^0) emission as a function of excitation laser wavelength. Measurements are made at injected carrier densities of about 10^{15} cm^{-1}, where (as the emission itself clearly shows), carrier-carrier scattering can be ignored. Representative scattering times are $\tau_{\Gamma\text{-}L} = 540$ fsec for 0.48 eV electrons and $\tau_{\Gamma\text{-}X} = 180$ fsec for 0.58 eV electrons. Recent calculations [3] and transport measurements [4] support these rates, which show that scattering to the X valley is much faster than scattering to the L valley for comparable energies.

Carrier-carrier scattering is measured using two picosecond lasers. At t=0, a pump pulse at 1.64 eV injects carriers into GaAs at densities up to 5×10^{16} cm^{-3}. About 30 psec later, a weak probe beam at 1.88 eV injects a smaller density of carriers. Comparison of the probe-excited hot (e,A^0) luminescence in the presence and absence of the pump shows directly how fast the probe-excited electrons scatter into the sea of pump-excited electrons. We find that the scattering rate increases linearly with density, with a scattering time of 500 fsec for an electron density of 2×10^{16} cm^{-3}, in agreement with theory.

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ThB-4 Determination of the LO phonon and the Γ→L scattering time in GaAs from CW hot luminescence spectroscopy, W. Hackenberg, G. Fasol, H. P. Hughes, *Cavendish Laboratory, Madingley Road, Cambridge CB3 OHE, UK,* E. Bauser and K. Ploog, *Max-Planck-Institut fur Festkörperforschung, D-7000 Stuttgart, W. Germany.*

Electron - LO phonon scattering time and the $\Gamma \to L$ scattering time for GaAs are of fundamental importance and they are parameters needed for device modelling. We have recently investigated CW hot luminescence from electrons high in the conduction band of GaAs recombining with holes on acceptors [1]. This technique [2] directly measures the steady state distribution of electrons in the conduction band. The steady state distribution reflects several ultra-fast processes: the LO phonon cascade, $\Gamma \to L$, $L \to \Gamma$, $\Gamma \to X$ and $X \to \Gamma$ scattering. We have recently also obtained band structure information and data on donors at higher conduction band minima using this technique [3]. In the present work, we compare our measured CW hot luminescence spectra with line shape calculations to obtain the LO phonon scattering time and the $\Gamma \to L$ scattering time from the lifetime broadening. We use a full double δ-function k-space integration, with a 16×16 **k.p** Hamiltonian for the band structure. The optical matrix elements are treated in Kane dipole model. We obtain results for electron kinetic energies in the range 150meV to 550meV. For the LO phonon scattering time we obtain a value of τ_{LO} = 135fs ± 15fs . Thus the scattering time we obtain is somewhat smaller than many values used now. The reason for this discrepancy might be, that in the present case there is little interference from electron-electron scattering because of the low induced carrier density in CW measurements. For the $\Gamma \to L$ scattering time we obtain values decreasing from around $\tau_{\Gamma \to L}$=100fs at an electron kinetic energy of 350meV to around $\tau_{\Gamma \to L}$ = 50fs for an electron energy of around 500meV. Thus our values lie fairly close to the value obtained by Zakharchenya et. al. using a magnetic depolarisation technique.

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ThP-10 The intervalley X_6-Γ_6 scattering time in GaAs measured by pump-IR-probe infrared absorption spectroscopy, W. B. Wang, N. Ockman, M. Yan, and R. R. Alfano, *Institute for Ultrafast Spectroscopy and Lasers, The City College of New York, New York 10031.* Intervalley scattering times place a lower limit on the relaxation times of conduction band electrons which determine the high frequency transport properties of semiconductors in high speed electronic devices and fast switches. Although there has been a number of investigations to study the intervalley scattering of $\Gamma \to L$, $\Gamma \to X$, $L \to \Gamma$ in GaAs, all of them only probed the dynamics of hot electrons in the central (Γ) valley. In addition, there has been no estimation for the scattering time of $X \to \Gamma$. In our measurement, infrared probe pulses were used to monitor the growth and decay of the population of hot electrons in the X_6 valley subsequent to excitation by a pump pulse as a function of pump-probe delay. This is the first direct measurement of the dynamics of electrons in a satellite valley in GaAs. Rate-equations, considering intra- and inter-valley scattering processes involving the Γ, L, and X valleys are used for analysis of the data. By fitting the solution of the rate equation to the direct measurement data, an intervalley $X_6 \to \Gamma_6$ scattering time of 500±350 fs is determined for the first time.

* Research is supported by the U.S.A. AFOSR under Grant 86-0031.

ThP-11 Picosecond photoluminescence measurements of hot carrier relaxation and Auger recombination in GaSb, P.A. Snow, D.J.Westland, J.F. Ryan, *Clarendon Laboratory, University of Oxford, Oxford,* and P. Maly *Dept. of Chemical Physics, Charles University, Prague.* Picosecond photoluminescence measurements of GaSb show that Auger recombination has a marked effect on the energy relaxation of photoexcited carriers. Furthermore, while we probe directly only those electrons lying within the Γ valley, we find that energy relaxation occurs predominantly within satellite valleys. These processes in GaSb are substantially different from those in other direct gap III-V semiconductors because of its unusual band structure: At 4K the conduction band minimum is at Γ, but there are low-lying minima at L, the energy difference being ~ 50meV. The fundamental energy gap . is almost exactly equal to the spin-orbit splitting of the valence band, and, consequently, the CHSH interband Auger recombination rate is anomalously high. For carrier densities ~ $10^{19}cm^{-3}$ we find that radiative recombination dominates at low temperatures (4K), but that Auger recombination becomes dominant at temperatures above 100K. We find that the luminescence risetime decreases from 120ps to < 3ps, the decay time decreases dramatically from ~ 1 ns to 40ps, and the total luminescence intensity is reduced by more than two orders of magnitude as the sample temperature is raised to 250K. Analysis of these data yield for the Auger coefficient a value of $10^{-28}cm^6s^{-1}$, which is approximately four orders of magnitude greater than that in GaAs. We estimate that under these experimental conditions Auger recombination contributes an effective input power to the carrier system of 10^8eVs^{-1} .

At early times after photoexcitation we observe very rapid carrier cooling. Calculations show that this is consistent with efficient relaxation of electrons within the L valleys: energy relaxation of electrons by LO phonon emission within L is enhanced relative to that in Γ because the much larger effective mass

($m_L/m_\Gamma \approx 20$) reduces the nonequilibrium phonon effect. However, at times ≥ 50ps the energy loss rate is remarkably low. This effect is explained quantitatively by Auger heating.

ThP-12 Nonthermalized carrier distributions in systems with extremely short lifetimes, Ralph A. Höpfel, *Institut für Experimentalphysik, Universität Innsbruck, A-6020 Innsbruck.* Optical excitation of electron—hole pairs far above the bandgap of a semiconductor generates monoenergetic carrier distributions that exist only for a small fraction of a picosecond. carrier—carrier scattering as well as emission of optical phonons change the initial distribution into a hot Fermi-Dirac distribution very rapidly ("thermalization"). For this reason, e.g., the time—integrated luminescence spectra are usually dominated by thermalized distributions (exponential decrease towards higher energies). In systems with extremely short carrier lifetimes (< 1 ps), however, the recombination time can be of the same order of magnitude or even shorter than the thermalization time. In this case the distribution functions, averaged over the whole lifetime, can be dominated by the initially monoenergetic, *nonthermalized* carrier distributions.

We report the experimental observation of such a situation, where the luminescence spectra give evidence for nonthermalized carrier distributions due to extremely short lifetimes. The luminescence of photoexcited carriers far above the bandgap of $Ga_{0.47}In_{0.53}As$ is studied with subpicosecond time resolution. In undamaged material the luminescence decays with characteristic times of 2 ps to 4 ps in the energy range between 1.9 eV and 1.4 eV, due to the rapid energy relaxation of electrons and holes far above the bandedges. In radiation damaged (He^+ bombarded) material, luminescence decay times as short as 0.9 ps are present, due to the ultrafast recombination induced by the radiation damage.

The luminescence spectra in these samples give evidence for extreme nonequilibrium distributions of the photoexcited carriers: The photoluminescence intensity is *higher at higher photon energies* (closer to the laser excitation energy). The luminescence spectra thus are "inverted", since the combined electron and hole energy distribution (dominated by the electrons) is not fully thermalized within the short recombination time. Examples of other systems (barrier layers, amorphous materials, nanostructures) with similar behaviour are given, and the possible applications (especially *intra*band lasers) are discussed.

ThP-13 Carrier cooling in nonpolar semiconductors studied with subpicosecond time resolution, A. Seilmeier, H. Roskos, B. Rieck, W. Kaiser, *Physik Department E11, Technische Universität München Arcisstrasse 21, D-8000 München 2, Germany.* In several publications reduced cooling rates of charge carriers have been reported for densities of ~ 10^{17} cm^{-3}. Two mechanisms have been discussed as possible cause: screening by free carriers and nonequilibrium phonon population generated by the cooling process. The importance of the phonon population may be investigated by experiments on nonpolar semiconductors like germanium. In this material carrier cooling proceeds via deformation potential interaction which is not screened efficiently by free carriers.

In the present paper carrier cooling in the nonpolar semiconductor germanium is studied. A thin single crystal of intrinsic Ge is excited at hν = 1.0 eV. The cooling of the carrier plasma is probed via transmission changes at the same frequency. A rapid rise of the signal is observed, reflecting the cooling of the carriers. Compared to previous investigations on germanium we work with substantially improved time resolution of < 1 ps and with high sensitivity which allows measurements at carrier densities as low as 10^{17} cm^{-3}.

In a recent note [1] we studied the temperature dependence of carrier cooling between 30 K and 300 K. A plasma of a few 10^{17} carriers per cm^3 was found to cool rapidly within a few picoseconds, independent of the lattice temperature. Here, the density dependence of the cooling process in germanium is discussed in the carrier range of 3×10^{17} cm^{-3} to 2.5×10^{18} cm^{-3}. Our data show that the time behavior of the transmission change is very similar for different carrier densities. The experimental results are compared with model calculations, taking into account the deformation potential interaction and neglecting nonequilibrium phonon populations. For carrier densities ≤ 10^{18} cm^{-3} (T_L = 30K) our data are in quantitative agreement with numerical curves based on interaction constants known from transport experiments. Obviously, for $n \leq 10^{18}$ cm^{-3} the cooling of carriers in Ge is not influenced by nonequilibrium phonon populations within the first 10 ps, where more than 90% of the excess energy is transferred to the lattice.

[1] H. Roskos, B. Rieck, A. Seilmeier, W. Kaiser, Appl. Phys. Lett. 3, 2406 (1988).

ThP-14 Hot carrier relaxation in InP and GaAs on a subpicosecond time scale, X. Q. Zhou, K. Seibert, W. Kütt. K. Wolter and H. Kurz *Institute for Semiconductor Electronics, RWTH Aachen, F.R.G.* In photoluminescence (PL) correlation experiments with fs laser pulses differences between electron- and hole-relaxation could be observed for the first time at carrier densities around 10^{17} cm^{-3} in III-V materials. The decay of PL-correlation signals taken in a wide spectral range below and above the excitation energy (2eV) is governed by differences in the lifetime of electrons and holes at the energy of emission in the Γ-valley, reacting sensitively to the removal of electrons from the Γ-valley via intervalley scattering. In addition, the reflectivity changes of highly excited (10^{19} cm^{-3}) InP and GaAs are studied at different wavelengths on a subpicosecond time scale, with main emphasis on the behaviour of electron distributions in the case of intervalley scattering (GaAs).

ThP-15 Relaxation of hot carriers in undoped and n-doped $Ga_{0.47}In_{0.53}As$ generated by subpicosecond IR-pulses, H. Roskos, B. Rieck, A. Seilmeier and W. Kaiser, *Physik Department E 11, TU München, Arcisstr. 21, D-8000 München.* Recently carrier cooling in $Ga_{0.47}In_{0.53}As$ has been studied by time-resolved photoluminescence and bleaching experiments with a time resolution of > 10 ps. Information on the later cooling process is obtained after a significant amount of the excess energy has been transferred to the lattice. For carrier densities ≥ 10^{17} cm^{-3} strongly reduced energy loss rates of the carriers were found.

In the present work carrier cooling in $Ga_{0.47}In_{0.53}As$ is investigated for the first time with subpicosecond time resolution. An undoped and a n-doped (8×10^{17} cm^{-3} Sn) bulk sample are studied at a lattice temperature of 30 K. An electron-hole plasma of a density of 5×10^{16} cm^{-3} to several 10^{18} cm^{-3} is generated by an ultrashort light pulse of photon energy hν = 0.98 eV. The pulse duration of 300 fs is comparable to the carrier-polar LO phonon scattering time. The increase of transmission of the samples is measured by a probe pulse of the same photon energy. In the undoped sample a rapid initial transmission change with a time constant of approximately 1 ps is observed. It is attributed to the cooling of the plasma starting from its maximum temperature of 600 K. At later delay times the time behavior of the transmission is more completely due to bandgap renormalization. The cooling of the charge carriers results in a reduction of the gap energy leading to an enhanced absorption of the sample. The n-doped sample exhibits a slower initial transmission change τ ≈ 3 ps). The longer time constant may be a consequence of screening and of a lower excess temperature of the created carriers due to rapid thermalization with the initially present cold carriers.

The experimental results are compared with model calculations. The transmission change of both samples during the first few picoseconds after excitation can be explained by a model taken into account screened Fröhlich interaction without assuming a density dependent carrier-LO phonon scattering time.

ThP-16 "Hot-carrier dynamics in Ge on single picosecond timescales: correlating Raman and reflectivity experiments within a self-consistent model, Jeff F. Young and P.J. Kelly *Division of Physics National Research Council Ottawa, Canada K1A OR6* and A. Othonos and H. M. van Driel *Department of Physics University of Toronto Toronto, Canada M5S 1A7.* Picosecond time-resolved Raman studies of athermal optical phonons in photo-excited Ge have revealed a number of interesting qualitative features associated with non-equilibrium carrier and lattice dynamics in elemental semiconductors. In the present work, we demonstrate that a more detailed model of the experimental conditions yields additional quantitative information about the carrier-lattice interaction. The model involves the solution of coupled Boltzmann equations for the hot electron, hole optical phonon populations as a function of time and position in the sample. The rate of energy transfer from each carrier species to optical phonon modes of arbitrary wave vector is calculated, and self-consistently integrated to yield the total cooling rate of the plasma. Temperature dependent ambipolar diffusion and electron-hole energy transfer processes are also included. Results for the calculated and measured non-equilibrium optical phonon population at the wave vector probed in the Raman experiments agree within a factor of two. The fact that non-equilibrium phonon populations of ~0.2 are generated for photo-excited carrier densities of ~ $1\times10^{18}cm^{-3}$, is traced directly to a kinematic focussing effect which restricts the range of modes through which the hot carriers can transfer their energy to the lattice. In addition, the model predicts a fast decay (~10 psec) associated with the optically excited carrier density near the sample surface, due to very rapid diffusion of the plasma while its temperature remains above ~ 3000K. Recent picosecond reflectivity measurements from photo-excited Ge will be presented as evidence is support of this prediction.

ThP-17 Transport of the photoexcited electron-hole plasma in InP, K. T. Tsen. G. Halama. O. F. Sankey. S.-C. Y. Tsen, *Physics Department, Arizona State University, Tempe, AZ 85287.* Transport properties of the photoexcited electron-hole plasma in InP have been studied by the time-resolved Raman scattering technique with ≅0.1μm spatial resolution and on a picosecond time scale. The experiments were carried out in a pump/probe configuration. The second harmonic of a cw mode-locked YAG laser was used to generate the electron-hole plasma. The pulse duration was ≅ 60ps and the repetition rate was 76MHz. Part of this beam was employed to synchronously pump a R6G dye laser operated at λ=565nm. The pulse duration of the dye laser which was used to probe plasma density through Raman scattering was ≅3ps. The spatial resolution was determined by the penetration length of these lasers in InP. i.e. ≅0.1μm. The plasma density ranging from 3×10^{16} to 5×10^{17} cm^{-3} was deduced from fitting of the Raman spectra with the plasmon-LO phonon scattering theory which took into account the contributions from free holes. Our experimental results have shown that perpendicular transport (i.e.. expansion into the bulk crystal) of the plasma can be very well described by a modified diffusion equation including the effect of drifting away from the surface based on a hydrodynamic model. The transient plasma density-time profiles were studied at T=300K and for an initial injected plasma density n ≅ 5×10^{17} cm^{-3}. The plasma has been found to drift away from the excitation spot with velocity v_d≅ 1.5×10^5 cm/sec.

ThP-18 Picosecond free carrier absorption and hot phonons in polar semiconductors, T. Elsaesser, R.J. Bäuerle, and W. Kaiser *Physik Department E11 der Technischen Universität München Arcisstr. 21, D-8000 München 2, Federal Republic of Germany.* A novel method for the investigation of hot carrier phenomena in III-V compounds is presented. The transient free carrier absorption of hot electrons is studied in the wavelength range from 3 to 10 μm to elucidate the characteristics of thermal relaxation. The experiments are based on the following technique: The electron gas in a n-doped sample is heated by an intense picosecond infrared pulse, which causes a redistribution of the carriers within the conduction band. The resulting change of free carrier absorption is monitored by a weak infrared probe pulse of variable time delay. The carrier density is constant in this type of measurement. As an example, we report results for a n-doped InAs crystal (electron density 1.5×10^{18} cm^{-3}) investigated at various lattice temperatures T_L. For T_L=70 K the absorption at a wavelength of 6.5 μm rises rapidly by 20 percent and decays – simultaneously with carrier cooling – within 80 ps to the initial value. The maximum carrier temperature has a value of approximately 550 K. A similar kinetics is found for T_L= 10 K whereas a smaller absorption change with a decay time of 40 ps is observed at T_L-300 K.

A detailed theoretical model of free carrier absorption is presented, which accounts quantitatively for the experimental data. Two mechanisms lead to a temperature dependence of the absorption coefficient: (i) the Fermi distribution function changes with increasing electron temperature; (ii) an excess population of longitudinal optical phonons created by carrier cooling couples in the absorption process and leads to an enhancement of absorption. Screening of the polar interaction is shown to be essential for the explanation of the relatively slow time scale of carrier cooling and the absolute value of the observed change of absorption. In addition data on the infrared absorption of hot electron-hole plasma in InAs are presented and compared to that on electron absorption.

ThP-19 Electron-electron scattering modifications of intervalley transition rates and ultrafast relaxation of hot photoexcited carriers in GaAs,* M. J. Kann, A. M. Kriman, and D. K. Ferry, *Center for Solid State Electronics Research Arizona State University, Tempe, AZ 85287-6206.* The femtosecond relaxation of photoexcited carriers in semiconductors is investigated by the use of ensemble Monte Carlo calculations coupled with a molecular dynamics approach for the carrier-carrier interaction, to probe various scattering mechanisms and the dynamic screening of hot carriers in semiconductors. The results indicate that the initial rapid relaxation occurs on a time scale of tens of femtoseconds in GaAs decreasing with increasing carrier density. We find the fast initial decay of carriers from the excitation volume occurs predominantly by electron-electron scattering. We found earlier that the Γ-L scattering rate is 75-80 fs (for 2 eV excitation) and the Γ-X scattering rate is about 50 fs. These results agree well with some, but not all, recent measurements. We use coupling constants that have been confirmed by several measurements (by different techniques). Even so, these numbers tend to be even faster than supported by careful calculation of the lifetime for carrier scattering out of the excitation volume done here. At a density for which the GaAs is degenerate (in equilibrium), the scattering out of the excitation volume is dominated by electron-electron scattering alone, and this lifetime decreases with increasing density. This decrease also agrees both in lifetime magnitude and in density dependence with recent experimental measurements. We find that the presence of electron-electron scattering modifies both the population transition rates and the carrier densities in the satellite valleys, primarily by its role on reshaping the energy distribution function of carriers in the central valley. These results indicate that great care must be used in estimating overall rates for carrier transfer to the satellite valleys, since the Γ-L population shift contains a significant fraction of electrons that reach the L valleys by way of the X valleys.

* Work supported in part by the Office of Naval Research.

ThP-20 A self consistent Monte Carlo method for the transient response of laser excited photoconductive circuits, R. Joshi and R. O. Grondin, *Center for Solid State Electronics Research, Arizona State University, Tempe, AZ 85287-6206.* We propose using an EMC embedded within a circuit solver to include the nonlinear transport of the photogenerated electron-hole plasma. In order to properly model experiments in non-equilibrium carrier transport [1,2] we have a bipolar model, use self-consistent electric field calculations, and include the screened anisotropic electron-hole scattering. Unlike previous simulations dealing with the steady state situations, we propose a new scheme to allow for transient changes in the net mobile charge by appropriately modifying the supercharge associated with each particle.

Nonuniform fields arising out of carrier separation effects are accounted for by using a Poisson solver self consistently. Figs. la and lb show the electric fields obtained from an EMC calculation for an N^+NN^+ structure. We shall present simulation results of actual experiments, and look at the behaviour of carrier velocities, line voltages and circuit currents. The use of superior P^+IN^+ structures is suggested for subsequent experiments. [1] C. V. Shank et al., Appl. Phys. Lett. 38, 104 (1981).
[2] K. Meyer et al., Appl. Phys. Lett. 53, 2254 (1988).

ThP-21 Effect of valence band anisotropy on the ultrafast relaxation of photoexcited carriers in GaAs,* M. A. Osman, M. Cahay and H. L. Grubin, *Scientific Research Associates, Inc., P.O. Box 1058, Glastonbury, Connecticut 06033.* The understanding of energy and momentum relaxation of carriers photoexcited by femtosecond laser pulses in semiconductors is a prerequisite for designing modern ultrahigh speed devices where the transit times are influenced by ultrafast relaxation processes. In earlier calculations we showed that at low carrier concentrations, the electron-phonon interaction dominated the cooling process, while at high densities the electron-hole interaction played the dominant role (Osman and Ferry, 1987). In this study we extend our earlier calculations which assumed spherical and parabolic heavy hole bands, to include the effect of warping of the heavy hole band.

The warping of the heavy hole band leads to significant anisotropy in the hole effective mass which changes from 0.45 along < 100 > to 0.98 along <111> (for $A = -6.98$, $B = -4.5$, $C = 6.2$ in the analytical expression for warped bands). This leads to a spread of 16 (6) meV in the energy of the electrons photogenerated from the heavy (light) hole bands by a laser pulse that provides 200 meV excess energy. Results will be discussed for different initial electron energy distributions where the corresponding holes are: (l) generated randomly, (2) generated along the <100> direction (corresponding to spherical parabolic band with $m^* = 0.45$), as well as effects of anisotropy on the cooling rates, thermalization process, and the distribution of hot phonons.

*Supported by the Office of Naval Research.

ThP-22 Femtosecond studies of intervalley scattering in GaAs and $Al_xGa_{1-x}As$, C. J. Stanton, *Department of Physics, University of Florida, Gainesville, FL 32607,* D. W. Bailey, K. Hess, *Coordinated Science Laboratory, University of Illinois, Urbana, IL 61801* M. J. LaGasse, R. W. Schoenlein, and J. G. Fujimoto, *Dept. of Electrical Engineering and Computer Science, MIT, Cambridge, MA 02139.* Results of femtosecond transient optical absorption experiments are compared to ensemble Monte Carlo simulations of the relaxation of photoexcited carriers. Emphasis is placed on the role of intervalley deformation potential scattering, both Γ-L and Γ-X. We show that this is a dominant relaxation mechanism on the fastest, 50fs time scale, for the electrons that are photoexcited by 2 eV and higher lasers.

The Monte Carlo simulations are compared with three different experimental techniques:

1). Transient absorption saturation measurements performed at 2eV pump and probe energies;
2). Pump and continuum probe techniques;
3). Tunable pump-probe experiments over the energy range of 1.91 to 2.14 eV.

Instead of extracting time constants from differential transmission spectra and accepting the compromise this imposes, we use the electron and hole distributions returned from the Monte Carlo simulations to directly obtain the differential transmission curves. From the comparison we obtain bounds on the intervalley scattering rates. The use of a tunable pump-probe laser experiment is extremely useful since it allows one to probe above and below the thresholds for transfer to the X and L valleys and thus turn on and off intervalley scattering.

In addition, we also discuss the role that electron-electron scattering and electron-POP scattering play on the observed fast decay. The effects of the holes are also considered. To accurately model the hole band structure, we use a full zone **k**·**p** theory which accounts for the warping and anisotropy of the hole bands and allows for an accurate determination of the **k** dependent overlap factors. The importance of the holes on the pump-continuum probe data is discussed.

ThP-23 Time-domain finite-difference study of hot carrier transport in GaAs on a subpicosecond scale, Yiqun Lu, R. Joshi, S. El-Ghazaly, and R. Grondin, *Center for Solid State Electronics Research, Arizona State University, Tempe Arizona 85287.* A variety [1-3] of subpicosecond experiments and measurements involve the excitation of transient electromagnetic waves. In order to design the experiment and correctly interpret its results, an accurate theoretical study of the hot carrier transport and the associated electromagnetic fields is needed. We are utilizing a time domain solution of Maxwell's equations [4] (which does not relay on the TEM wave approximation) in a study of one such experiment, in which a transient is excited in a microstrip-line fabricated on a GaAs substrate, and observed electro-optically. The physics of interest is the photoconductive transient which excites the line. In this approach, Maxwell's equations are discretized in time and over a three dimensional mesh in the real space using the finite difference technique. This solution will be coupled to a Monte-Carlo model of hot carrier transport. Initially, the spatial and velocity distributions of the excited carriers will be used to obtain the new electromagnetic fields. The new fields will be fed into the Monte-Carlo model to update the carrier distribution after a very short time step (ΔT). This process may be repeated until the desired length of time is covered.

This method is very powerful and general. Once the code is developed, it can be applied to investigate some devices operating at very high frequencies simply by specifying the doping concentrations and electrode locations in space.

[1] P. M. Downey et. al., Picosecond Electronics and Optoelectronics I. New York: Springer-Verlag, 1985.
[2] G. Mourou et. al., Picosecond Electronics and Optoelectronics II. New York: Springer-Verlag, 1987.
[3] M. C. Nuss et. al., Picosecond Electronics and Optoelectronics III. New York: Springer-Verlag, 1987.
[4] X. Zhang et. al., IEEE Trans. Microwave Theory Tech., MTT-36, pp. 1775-1787, 1988.

ThP-24 Electron transport in semiconductors under a strong high frequency electric field, W. Cai, P. Hu, T. F. Zheng, B. Yudanin, *Department of Physics, City College of the City University of New York, New York, New York 10031,* M. Lax,* *Department of Physics and the Graduate Center of the City University of New York, New York, New York 10031, and AT&T Bell Laboratories, Murray Hill, New Jersey 07974.* We propose an analytical approach to study the nonlinear effects of electron transport when a strong high frequency (HF) electric field is applied together with a DC electric field. When a HF field is applied, the trajectory of an electron between scatterers is no longer straight. An oscillating drift motion is superposed upon the random motion of electron caused by the scattering processes. The transport of electrons after time t, dependents not only on the condition at time t, but also on the drift motion of the electrons before t. This memory effect is included in our approach. The dynamic equation we used, therefore, is different from that of the Boltzmann equation. (If the memory effect for the drift motion of electrons is neglected, our formulas reduce to the Boltzmann approach). Using the above approach we study the HF "steady" state transport. Assuming the distribution function of electrons in the relative coordinates is a Maxwellian, we obtain a set of evolution equations to determine the DC component and each harmonic components of electron drift velocity and the electron temperature. We have used this approach to calculate the electron transport in an n-GaAs sample. A microwave frequency ν= 35 GHz is chosen as the base frequency. We find that when only the electric field with base frequency E_1 is applied, DC conductivity declines about 5% from its static value, for HF fields up to E_1=l kV/cm. This result is in agreement with that in Ref. 1. Surprisingly, if a second harmonic electric field is applied together with the first harmonic one (with the same phase), DC conductivity decreases dramatically with increase of HF field, and definitely becomes negative when E_1 and E_2 are near 1 kV/cm, namely, a weak positive DC potential drop can produce a negative DC current. This phenomenon was shown by experiments in Ref. 2.

[1] K. Ashida, M. Inoue, and J. Shirafuji, J. Phys. Soc. Jpn. 37, 408 (1974).
[2] J. Pozhela, "Plasma and Current Instabilities in Semiconductors" Intern. Ser. Sci. Solid State, Vol. 18 (Pergamon, Oxford 1981); T. J. Banys, I. V. Parsheliunas, and Y. K. Pozhela. Liet. Fis. Rinkinys 11, 1013, (1971); Fis. Tekh. Polupr 5, 1990 (1971).

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FA-1 Overshoot saturation in ultra-short channel FETs due to minimum acceleration lengths,* J. M. Ryan, J. Han, A. M. Krima. and D. K. Ferry, *Center for Solid State Electronics Research, Arizona State University, Tempe 85287,* P. Newman, *U. S. Army Electronics Technology and Devices Laboratory Fort Monmouth, NJ 07703.* Ultra-submicron GaAs MESFETs and HEMTs have been fabricated with gate lengths ranging from 25 nm to 80 nm using an electron-beam lithography process. The MESFETs were fabricated on wafers doped at 2×10^{17} cm^{-3} and 1.5×10^{18} cm^{-3} with active layer thicknesses of 250 nm and 60 nm, respectively. The HEMTs were fabricated on modulation doped material both with and without a spacer layer. The devices were tested at both d.c. and microwave frequencies (2-20GHz). Measurements of the transconductance, and the inferred transit velocity, as a function of the effective gate length show a minimum in these quantities near 55 nm. The rise in transconductance below this gate length is attributed to the onset of velocity overshoot in the channel region, and both the inferred transit velocity and the variations between the lightly doped samples and the heavily doped samples support this interpretation. For gate lengths below about 40 nm, however, the transconductance again drops. This latter is supported by plotting the f_T of these devices versus gate length, in which most devices fit a common saturation velocity except for the shortest devices. We attribute this drop to the existence of a minimum acceleration length needed for the carriers to reach the high values of the overshoot velocity. We have investigated this behavior with a transient transport model based upon a parametrized velocity autocorrelation function incorporating both energy and momentum relaxation rates. The results of this model yield qualitative agreement with both the measurements and the interpretation given above.

* Work supported in part by the Army Research Office.

FA-2 Ensemble Monte Carlo simulation of sub-0.1μm gate length GaAs MESFETs, Masaaki Kuzuhara and Tomohiro Itoh, *Microelectronics Research Laboratories, NEC Corporation, 4-1-1 Miyazaki, Miyamae-ku, Kawasaki 213, Japan,* Karl Hess, *Coordinated Science Laboratory, University of Illinois, Urbana, Illinois 61801.* We have simulated, for the first time, the dynamics of electron transport in GaAs MESFETs with a gate length down to 10nm, using a self-consistent electric-field ensemble Monte Carlo model. The model incorporates the complete Γ-L-X band structure including the effect of nonparabolicity. The scattering mechanisms considered are electron-electron scattering, Polar optical phonon scattering, equivalent and nonequivalent intervalley scattering, and ionized impurity scattering.

The FET structure consists of a 25nm GaAs n-type (2×10^{18} cm^{-3}) channel layer grown on an undoped GaAs or $Al_{0.3}Ga_{0.7}As$ buffer layer. Both source-to-gate and gate-to-drain spacings are held constant at 150nm with a gate length ranging from 10 to 200nm. The effect of degeneracy is taken into account in the heavily-doped GaAs channel region. [1]

The peak transconductances of 700mS/mm are obtained with a gate length of 50nm for both GaAs and $Al_{0.3}Ga_{0.7}As$ buffered structures. The transconductance (g_m) for the GaAs-buffered FET is degraded to 370mS/mm when a gate length is further reduced to 10nm because of the pronounced current component flowing into the GaAs buffer layer. This undesirable short channel effect is considerably alleviated by introducing an $Al_{0.3}Ga_{0.7}As$ buffer layer. The g_m for the $Al_{0.3}Ga_{0.7}As$-buffered FET remains over 600mS/mm even with a gate length of 10nm. These results clearly show the importance of heterojunction buffered structures for achieving excellent device characteristics in sub-0.1μm gate length GaAs MESFETs. The effect of Pauli's principle on the electron transport dynamics and the more detailed role of $Al_{0.3}Ga_{0.7}As$ buffer layers on the device characteristics will be discussed.

[1] P.Lugli and D.K.Ferry, IEEE Trans. Electron Devices, ED-32, 2431(1985).

FA-3 Lattice gas theory of semiconductor transport, M. Rieger and P. Vogl, *Institut für Theoretische Physik, Universität Graz, A-8010, Austria.* We present a new technique to study semiclassical nonlinear transport in semiconductors. The approach opens up new ways to quantitatively simulate the carrier dynamics in the presence of complex boundary effects, inhomogeneous charge distributions and carrier-carrier scattering.

The method is based on a real space, nearest neighbor, lattice gas simulation of the Boltzmann equation. The system is updated according to microscopic rules for the field-dependent intercollisional trajectories and scatterings. The scattering rules are designed to be in accordance with the quantum mechanic scattering probabilities. The algorithm uses pure integer arithmetic; therefore no roundoff errors can accumulate. The calculations resemble a real-space Ensemble Monte Carlo simulation with a very large ensemble (typically 10^6 particles) but a crude discretization of the microscopic particle trajectories. Physical quantities, such as the local carrier concentration, energy, and drift velocity, are obtained by averaging over many lattice sites.

The method provides a highly efficient way to utilize concurrent computer architectures with multiple parallel processors. On a single standard vector processor, we find a MESFET simulation to be at least two orders of magnitude faster than an equivalent Monte-Carlo calculation. We present detailed comparisons of our technique with standard Monte-Carlo and semiconductor-equation approaches. Excellent agreement is found for velocity-field characteristics and for charge and field distributions in a MESFET. We are presently investigating current filamentation and generation/recombination in two and three dimensional systems.

FA-4 Novel mobility-controlled switching effect in a heterojunction structure, Federico Capasso, Fabio Beltram, and Roger J. Malik, *AT&T Bell Laboratories, Murray Hill, NJ 07974.* We demonstrate a new switching effect in a heterojunction device based on real-space transfer [1] of hot electrons from a low mobility to a high-mobility channel. With a load resistor in series the devices exhibit S-shape type I-V characteristics. So far, real space transfer in parallel transport has been studied only in the context of electrons being transferred from a high mobility (typically modulation doped GaAs) to a low mobility (typically doped $Al_xGa_{1-x}As$) channel thus producing negative differential resistance. [1]

The structure was grown by e-beam Molecular Beam Epitaxy and consisted of a n (1×10^{17} cm^{-3}) GaAs channel 700-Å thick separated from an undoped GaAs channel 1500-Å thick by a 500-Å compositionally graded $Al_xGa_{1-x}As$ undoped barrier with x ranging from 0.2 (on the side of the doped channel) to 0.1. On the other side of the undoped GaAs channel an undoped 1000-Å $Al_{0.35}Ga_{0.65}As$ isolation barrier was grown followed by a n^+ 300-Å-thick GaAs layer that concluded the growth. Contacts were provided so that the two channels are in parallel. A Schottky contact was deposited on the top layer (much like the gate in a FET configuration).

Electrons were heated up in the doped GaAs channel by applying bias. In the temperature range (20K — 300K) of our apparatus and at fields ~ 1 kV/cm we observed an abrupt jump in the current-voltage (I-V) characteristics due to the real-space transfer of hot electrons from the low-mobility n-GaAs channel to the high-mobility i-GaAs channel. The magnitude and the abruptness of the current jump can be quantitatively understood in terms of the high ratio of the mobilities in the two layers (≅ 30 at 77 K) and the nonlinear heating of carriers. Just before this feature the I-V showed negative differential reflectance. The latter is a well known effect [1] due to the real-space transfer of electrons from the n-GaAs channel to the (compositionally graded) low mobility $Al_xGa_{1-x}As$ layer. To further substantiate our interpretation we performed also capacitance-voltage (C-V) measurements. The doping and thickness of the layer ending the growth were adjusted so that at zero gate-source bias the depletion region slightly penetrates into the lower mobility doped channel. The gate-source capacitance was measured as a function of the drain-source voltage at zero gate bias. We found that corresponding to the jump in the I-V, the C-V exhibited an increase in quantitative agreement with that expected from charge transfer of hot carriers between the two channels.

[1] K. Hess, H. Morkoc, H. Schichijo, and B. G. Streetman, Appl. Phys. Lett. 35, 469 (19 79).

FB-1 Summary of the Conference, Peter Price, *Yorktown Heights.*

FB-2 The future of hot carriers, G. J. Iafrate, *Fort Monmouth.*

PDP-1 Hot electron focusing with quantum point contacts, J. G. Williamson, H. van Houten, C. W. J. Beenakker, L. I. A. Spendeler, B. J. van Wees, and C. T. Foxon, *Eindhoven.* Ballistic transport of electrons, with excess energy of the order of the Fermi energy, has been observed over several microns in the two dimensional electron gas of a GaAs-AlGaAs heterostructure. Quantum point contacts in the electron focusing geometry [1] have been used as a novel magnetic spectrometer to measure the kinetic energy of injected electrons. In this experiment electrons are injected through a point contact and focused onto an adjacent point contact (the collector) by a perpendicular magnetic field. Electrons injected with energy E are focused at magnetic field values B which are integer multiples of $(2mE)^{1/2}$ $(2/eL)$, with L the point contact separation. In a differential measurement, focusing peaks in the collector voltage are observed at magnetic field values corresponding to energies of the Fermi energy plus (or minus) an additional energy supplied by an external DC voltage source. Both hot electrons and cool missing electrons (holes in the conduction band) can be studied by this technique. Quantum interference fine structure (which is superimposed on the focusing peaks at low bias [2] becomes suppressed as the voltage is increased. The observed energy gain is linear in the applied DC voltage and the slope allows a determination of the local voltage drop over the injecting point contact. Hence the quantized point contact resistance can be measured directly without an additional background resistance. No evidence for energy relaxation is found on a length scale of 1.5 μm, for excess energies of up to 50% of the Fermi energy of 14 meV.

[1] H. van Houten *et al.*, Europhys. Lett. **5**, 721 (1988); Phys. Rev. B (April 1, 1989).
[2] C. W. J. Beenakker *et al.*, Europhys. Lett. **7**, 359 (1988).

PDP-2 Length dependent hot electron noise in GaAs and InP at 80 K, V. Bareikis, J. Liberis, A. Matulionis, R. Miliušytė, J. Požela, and P. Sakalas, *Semiconductor Physics Institute, Academy of Sciences of the Lithuanian SSR, Vilnius.* The dependence of drift velocity on sample length (and the related overshoot due to intervalley transfer) is well known in InP and GaAs at high electric field. We have studied the length dependent behavior of hot electrons in the absence of intervalley transfer. The noise measurements are found to be the most appropriate.

The hot electron noise temperature and spectral density of current fluctuations are measured at 10 GHz microwave frequency. Length dependent behavior is studied in slightly doped micron long samples (10^{15} cm^{-3}, 1 to 10 μm). The experimental results are compared to those of Monte Carlo simulation.

Long samples show the specific noise source which dominates in a rather wide range of electric field (e.g., from 0.5 to 5 kV/cm in InP). This noise is not due to intervalley transfer. It results from the long-range high velocity fluctuations associated with the polar runaway which fails because of either large-angle scattering (e.g., due to acoustic phonons) or the sample length. Because of the latter reason the fluctuations are suppressed in short samples. The higher intervalley separation energy in InP as compared to GaAs favors the failed runaway fluctuations and leads to the wider field range where they dominate.

PDP-3 Phonon-assisted tunneling of photoexcited carriers from InGaAs quantum wells in applied electric fields, M. G. Shorthose, J. F. Ryan, *Clarendon Laboratory, Oxford*, A. Moseley, *Plessey Res., Caswell*. We have measured photocurrent spectra and photoluminescence decay times of InGaAs quantum well *pin* structures as a function of temperature under different conditions of illumination intensity and applied electric field. Our results give clear evidence that phonon-assisted tunneling of carriers is the dominant escape mechanism. At low temperatures (50K) we observe a threshold field for detection of photocurrent in a 5nm quantum well at 6.5×10^4V-cm^{-1}. This threshold field decreases by nearly an order of magnitude with increasing temperature up to 300K. The photocurrent in fact shows three threshold fields which separate different domains of behaviour. At low temperature and low field we observe strong bleaching of excitonic features in the photocurrent spectra with increasing illumination intensity; for biases well above the threshold value we do not observe this bleaching. Correlation of these results with simultaneous photoluminescence measurements shows that the photocurrent behaviour is due to competing dynamical processes – exciton formation, dissociation and recombination, and tunnelling of carriers from the well. By direct measurement, we observe the luminescence decay time to decrease from 4.0ns at low field, where recombination dominates, to 1.6ns for a field of 6.5×10^4V-cm^{-1}, thereafter rapidly falling to less than 0.1ns for fields greater than 9.5×10^5V-cm^{-1}, where carrier tunneling dominates and the photocurrent reaches its maximum value.

Our interpretation of the results is supported by extensive calculations of the carrier dynamics within the structure. We have determined the complex energies of the quasi-bound states in applied electric field, and obtain the direct tunnelling lifetime from the imaginary term. This rate is too low to explain the experimental results. The LO phonon-assisted tunnelling rate is found to be substantially higher, and its temperature variation accounts for the shift of the observed bias threshold to lower values with increasing temperature.

PDP-4 Global bifurcation and hysteresis of self-generated oscillations in a microscopic model of nonlinear transport in p-Ge, G. Hüpper, E. Schöll, *Institut für Theoretische Physik, Rheinisch-Westfälische Technische Hochschule, Aachen, W. Germany*, and L. Reggiani, *Dipartimento di Fisica dell' Università, Modena, Italy*. Nonlinear self-generated oscillations in the regime of impact ionization of impurities by hot carriers have recently become the subject of extensive theoretical and experimental research [1]. Previous theoretical approaches were mainly based upon simple phenomenological transport models using such gross simplifications as a constant mobility and energy relaxation time [2]. Here we attempt an understanding of these phenomena on a more microscopic level of description using energy-dependent momentum and energy relaxation times obtained from a Monte Carlo simulation for p-Ge at 8 K. With this a set of coupled dynamic equations for the mean carrier density, the mean carrier energy, and dielectric relaxation of the electric field is derived, and studied analytically and numerically. The static current - field characteristic displays N-type negative differential conductivity induced by impact ionization of a shallow acceptor level and optical phonon emission. In the positive differential conductivity region of this characteristic we find a subcritical Hopf bifurcation and two novel types of global bifurcations of limit cycle oscillations (collision of two limit cycles and saddle-focus bifurcation on a limit cycle) and hysteresis between oscillatory and stationary states. Such behavior was not obtained in previous models, but is consistent with recent experimental findings.

[1] E. Schöll: Nonequilibrium Phase Transitions in Semiconductors (Springer 1987).
[2] E. Schöll: Sol. State Electron. 31, 539 (1988).

PDP-5 Addition of ballistic resistors, P. Beton, B. R. Snell, A. Neves, P. C. Main, J. R. Owers-Bradley, L. Eaves, M. Henini, O. H. Hughes, *University of Nottingham, United Kingdom*, S. P. Beaumont and C. D. W. Wilkinson, *University of Glasgow, United Kingdom*. We have measured the series resistance of two ballistic resistors 0.5 µm apart. Each independent resistor is constructed with a horn channel and has good resistance quantization in zero field. We are able to measure the potential in the region between the resistors. We find that under all conditions the electron transport is at least 80% ballistic and that under some circumstances the motion is essentially totally ballistic. The effect of a magnetic field on the resistance is investigated and the results compared with the predictions of Beenakker and van Houten.

We have also studied the series resistance of two ballistic resistors at 90° to each other. In the absence of a magnetic field these add together totally classically with the series resistance equal to the sum of the individual resistances. However, the application of a small magnetic field (B~1T) and the establishment of edge state conduction transforms the situation from the classical to the ballistic case, thereby monitoring the creation of the edge states.

PDP-6 Wavepacket propagation in an arbitrary two-dimensional configuration, M. Cahay, J. P. Kreskovsky and H. L. Grubin, *Scientific*

Research Associates, Glastonbury, CT. We study the diffraction of a two-dimensional Gaussian wavepacket through a rectangular aperture in a finite wall (slit experiment). Our numerical simulations show that part of the wavepacket actually tunnels through the potential barrier, resulting in a deformation of the diffraction pattern. The latter can only be clearly seen for small time duration (<2ps). The deformation of the diffraction pattern through the slit in the presence of small imperfections in the potential energy profile is also examined. It is found that the diffraction pattern is quite insensitive to the dimensions of the asperities in the wall as long as their dimensions are small compared to the electron wavelength. Such numerical simulations are quite informative in addressing the feasibility of a newly proposed Quantum Diffraction FET (Bernstein and coworkers), whose mode of operation is based on quantum diffraction of electrons through a narrow slit in the gate.

Our algorithm consists in an Alternating Direction Implicit (ADI) scheme to solve the time-dependent Schrödinger equation in a two-dimensional domain of arbitrary rectangular geometry. The technique can be used with non-uniform grid spacings, allows for an explicit time-dependence of the potential energy profile and can readily be extended to include the presence of an external magnetic field and to three-dimensional configurations.

PDP-7 Hot electron scattering rates in quasi-equilibrium electron-hole plasmas calculated using full dynamic screening, J. F. Young, P. J. Kelly and N. L. Henry, *National Research Council, Canada* For sufficiently low densities of optically injected electron-hole plasmas in GaAs, the electrons and holes exchange energy primarily with the optical phonon modes of the host, and the relaxation processes can be described using a single-particle picture of the non-equilibrium state. At some "critical" density, Coulomb mediated electron-electron and electron-hole scattering can become comparable in strength to the carrier-phonon interactions, and at this point the hot carrier problem becomes manifestly many-body in nature. In a *general* non-equilibrium state it is extremely difficult, either experimentally or theoretically, to define this "critical" density. Therefore, to make progress towards understanding these complex many-body processes it makes sense to consider the case of hot electrons interacting with quasi-equilibrium electron-hole plasmas which have equal and well-defined temperatures, but unequal chemical potentials. Kash *et al.* [1] recently experimentally realized such a system and were able to deduce the "critical" plasma density at which the electron-plasma interaction strength becomes equal to the electron-LO phonon interaction strength. In this contribution we develop a general formulation of the hot electron scattering problem in terms of the multicomponent, quasi-equilibrium dynamic structure factor of the system. Using the same basic formalism we compare calculations of the carrier-carrier and carrier-lattice scattering rates using static and full dynamic screening (within the RPA), both with and without the lattice polarizability included. We find that agreement with the results of Kash *et al.* is obtained only by using the full RPA calculation, including the lattice contributions. We also demonstrate that dynamic screening strongly enhances the coupling between the hot electron and density fluctuations associated with inter-valence band (heavy-to-light) transitions, rendering them as important as intra-conduction band and LO phonon scattering processes under the relevant experimental conditions.

[1] J. A. Kash, P. G. Ulbrich and J. C. Tsang, paper ThB-3 of this conference.